NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

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RTO TECHNICAL REPORT **TR-SET-114**

Urban, Indoor and Subterranean Navigation Sensors and Systems

(Capteurs et systèmes de navigation urbains, intérieurs et souterrains)

Final Report of Task Group RTG-065.

Published November 2010

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Table of Contents

List of Figures

List of Tables

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Urban, Indoor and Subterranean Navigation Sensors and Systems

(RTO-TR-SET-114)

Executive Summary

The Research Task Group (RTG) on "Urban, Indoor and Subterranean Navigation Sensors and Systems" was formed to focus on how to enhance NATO military effectiveness through the improved use of advanced navigation sensor technologies. This report summarizes the work of the RTG, includes a description of the products generated by the group, and provides a technical overview of new and emerging navigation sensor and system technologies that will impact future military operations worldwide.

During the existence of the RTG from 2006 to 2009, the group organized a Symposium titled "Military Capabilities Enabled by Advances in Navigation Sensors" held in Antalya, Turkey in October 2007. Navigation experts from many NATO and Partners for Peace countries participated. The Task Group also organized a Lecture Series, "Low Cost Navigation Sensors and Integration Technology" which was held in 6 cities in several NATO nations in 2008 and 2009, and due to increased interest the Series will be held in four more cities in 2010. The Task Group also produced a handbook on advanced navigation technologies, entitled "Basic Guide to Advanced Navigation, 2nd Edition" that follows the first edition published by NATO RTO in 2004. The handbook is replete with numerous illustrations and was produced with the intent of providing an overview to those who wish to know more about navigation technology, but are not experts in the field. This report is the final product of the group.

This report summarizes recent advances in navigation sensor technology, including Inertial Navigation Systems (INS), Global Navigation Satellite Systems (GNSS), and other Radio Frequency (RF) and non-RF navigation aids. In particular, significant progress in the area of inertial components based on MEMS (Micro-Electromechanical System) technologies is forecast to have a huge impact in future navigation systems. Much attention is paid to other sources of navigation information such as imaging systems, database matching systems, pseudolites and other signals of opportunity. Considerable research is being done to study the mysterious techniques that animals use to navigate in an attempt to understand and exploit such methods. The report also describes recent advances in sensor data integration, such as ultra-tight coupling and particle filters.

The report concludes with a description of the enhanced military capabilities that will result, such as higher situational awareness, more reliable operations in urban, indoor and subterranean environments, enhanced unmanned-platform navigation, and greater weapons effectiveness. Many of the networked, collaborative systems being developed today implicitly assume an exact knowledge of position, orientation and time data obtained without detailing the source of such perfect information, especially in GPS denied environments.

We are still many years away from systems that will fulfil the requirements of every conceivable platform at a realistic size and cost but, as this report details, there continue to be exciting advances in navigation sensors and integration techniques.

Capteurs et systèmes de navigation urbains, intérieurs et souterrains

(RTO-TR-SET-114)

Synthèse

Le groupe opérationnel de recherche (RTG) sur les « Capteurs et systèmes de navigation urbains, intérieurs et souterrains » a été constitué pour se consacrer à l'amélioration de l'efficacité militaire de l'OTAN par une meilleure utilisation des technologies des capteurs de navigation. Le présent rapport dresse le bilan des travaux du RTG, comprend une description des résultats obtenus par le groupe et donne un aperçu technique des technologies nouvelles et émergentes des capteurs et systèmes de navigation qui auront un rôle à jouer dans les futures opérations militaires conduites à l'échelle mondiale.

Pendant les trois années d'existence du RTG, de 2006 à 2009, le groupe a organisé un symposium intitulé « Capacités militaires permises par les progrès réalisés dans le domaine des capteurs de navigation » qui s'est tenu à Antalya en Turquie en octobre 2007. Des experts de la navigation issus de nombreux pays de l'OTAN et du Partenariat pour la paix y ont participé. Le groupe de travail a également organisé des conférences sur le thème « Capteurs de navigation à bas coûts et technologie d'intégration » qui se sont tenues dans 6 villes de différents pays de l'OTAN en 2008 et 2009, et par suite de leur intérêt croissant, des conférences auront lieu dans quatre autres villes en 2010. Le groupe de travail a également produit un document traitant des technologies de navigation évoluées intitulé "*Basic Guide to Advanced Navigation, 2nd Edition*" (Guide fondamental sur les moyens de navigation évolués, 2ème édition) qui fait suite à la première édition publiée par la RTO de l'OTAN en 2004. Le document est agrémenté de nombreuses illustrations et a été publié pour donner une vision d'ensemble aux personnes qui souhaitent en savoir plus sur la technologie de navigation sans pour autant être experts en la matière. Ce rapport est le produit final du groupe.

Ce rapport fait un état des progrès récents réalisés dans la technologie des capteurs de navigation, qui comprend les Systèmes de Navigation Inertielle (INS), les Systèmes Globaux de Navigation par Satellite (GNSS), et d'autres moyens de navigation par radiofréquences (RF) ou sans RF. En particulier, les progrès significatifs réalisés dans le domaine des technologies des composants inertiels à base de MEMS (systèmes micro-électromécaniques) devraient avoir un impact considérable sur les futurs systèmes de navigation. D'autres sources d'informations de navigation appellent l'attention : c'est le cas des systèmes d'imagerie, des systèmes de croisement de bases de données, des pseudolites et autres signaux d'opportunité. De nombreuses recherches sont faites pour étudier les mystérieuses techniques de navigation utilisées par les animaux pour tenter de comprendre et d'exploiter leurs méthodes. Le rapport décrit aussi les récentes avancées réalisées sur l'intégration des données des capteurs, comme le couplage ultraserré et les filtres à particules.

Le rapport conclut par une description des capacités militaires améliorées qui en découleront, comme une meilleure connaissance de la situation, des opérations plus fiables en milieu urbain, intérieur ou souterrain, une navigation améliorée des plateformes sans pilote, et une plus grande efficacité des armes. De nombreux systèmes en réseau et en collaboration développés à l'heure actuelle s'approprient implicitement une connaissance exacte de la position, de l'orientation et des données temporelles obtenues sans détailler la source de ces informations précises, en particulier dans les milieux ou les signaux GPS ne sont pas disponibles.

Nous sommes encore à des années des systèmes qui rempliront totalement les exigences de chaque plateforme imaginable avec une taille et un coût réalistes mais, comme cela est dit dans ce rapport, il continue d'y avoir des avancées intéressantes dans le domaine des capteurs de navigation et des techniques d'intégration.

Chapter 1 – INTRODUCTION

A previous Research Task Group (SET-054/RTG-30) studying "Emerging Military Capabilities Enabled by Advances in Navigation Sensors" [1], conducted a program of work from 2001 to 2004 in which NATO experts from government, academia, industry and the military produced an analysis of future navigation sensors and systems whose performance improvements, decreasing cost, volume, and weight could meet critical, future military needs.

Operations in dense and potentially confusing urban areas are increasingly important tasks for current and future military forces. Maintaining tactical situational awareness of assets in such environments is difficult with much of today's technology, primarily because of the reliance on conventional GPS as a primary positioning system. GPS is not particularly well suited for use indoors or in other areas of signal blockage such as in dense urban environments. A need for robust navigation systems for urban, indoor, subterranean or other environments is critical to minimize casualties and collateral effects. However currently deployed systems do not have the location determination accuracy required to support such requirements in dense urban environments. This is a particularly difficult problem and one that requires new and innovative ideas. Integration and networking with all available sensors are seen as necessary to provide robust navigation and an enhanced situational awareness capability in such environments.

Advances in low cost, Micro-Electromechanical Sensors (MEMS) have continued. In addition improvements in satellite navigation systems, and new and innovative positioning systems such as networked navigation, ultra-wideband, map making/matching systems and various distance and velocity measurement devices, etc., continue to evolve. Thus a follow-on Task Group (SET-114/RTG-065) was established in 2006, following an exploratory team meeting in 2005, to continue to identify and to evaluate recent advances as well as new applications and potential benefits to military operations and operational concepts. The focus of the Task Group was to explore technologies that will enhance NATO military effectiveness, particularly in the challenging indoor, urban and subterranean environments, through the improved use of advanced, low-cost navigation sensor technologies. The results will enable increased situational awareness, greatly increased operational tempo, and robust navigation in the face of countermeasures or otherwise degraded environments in a highly mobile, networked environment.

The work conducted by the Task Group included the following:

1) A Symposium was conducted in the fall of 2007 to bring out the emerging ideas in the NATO community and convene subject matter experts. About 30 papers from six NATO nations covering a broad spectrum of navigation-related technology were presented to an enthusiastic audience in Antalya, Turkey. The information obtained was documented in the Meeting Proceedings [2] and summarized in this report.

2) A Lecture Series was given, covering advanced navigation technology and applications in urban and indoor environments with lectures on advances in inertial sensors, Global Navigation Satellite Systems (GNSS) receiver technology, and innovative navigation systems. The lectures were presented in 6 cities from 2008 – 2009 and will be presented in four more in 2010. The papers from the Lecture Series were published by NATO [3] and are summarized in this report.

3) A high-level handbook, entitled "Basic Guide to Advanced Navigation – 2nd Edition", that gives an overview of various forms of navigation technologies currently or soon to be available, was completed and made available on the NATO website [4] since May 2009. The handbook is in the NATO publication process and expected to be available in printed form by mid-2010. Portions of the handbook are included in this report.

This report begins with a detailed review of each of the above activities in Chapter 2. A summary of the navigation sensor and system technologies investigated is presented in Chapters 3 and 4. This material is preceded by a summary table (Table 3-1) that updates a similar table in the previous Task Group report. Chapter 5 expands upon emerging military capabilities enabled by the sensor and system developments, and Chapter 6 provides a summary. Annex A reviews the Symposium in more detail and Annex B reproduces the overview paper by G. Schmidt at the Lecture Series which provides an exceptional summary of recent advances in inertial and GPS systems and their integration.

Chapter 2 – RTG ACTIVITIES

2.1 THE SYMPOSIUM

The Sensors and Electronics Technology (SET) Panel Symposium on "Military Capabilities Enabled by Advances in Navigation Sensors" was held in Antalya, Turkey, 1-2 October 2007. The purpose of the Symposium was to bring together subject matter experts in the field of navigation sensors and integration technology to present emerging systems concepts to the NATO community. The emphasis of the Symposium was on navigation in indoor, urban and subterranean environments where GNSS signals are not available. In today's asymmetric warfare, robust and accurate navigation systems in such difficult environments are essential to increase effectiveness and make possible the application of new operational concepts. The Symposium was a follow-up to the Symposium organized by the previous group in 2002 [5].

Dr. Neil Barbour produced an independent review of the Symposium summarizing the presentations and discussions. Portions of this review are reproduced in Annex A and can be found in its entirety in the Symposium proceedings published as NATO RTO document MP-SET-104 [2].

The Symposium identified several applications requiring the capabilities provided by advanced navigation sensors and systems:

- Networked and collaborative operations;
- Autonomous land, sea and air vehicles;
- Personal navigation;
- Increased situational awareness;
- Optimal deployment of assets;
- Location of targets/threats;
- Operations in hostile environments with potential jamming and spoofing;
- Operations in indoor, urban and subterranean environments; and
- Time transfer/synchronization.

The enabling technologies for robust, accurate and affordable navigation systems were discussed by the subject matter experts under the following sessions.

2.1.1 Sessions 1 – 2: Non-GNSS Systems and Concepts

Several methods of navigation that do not rely on satellite navigation systems were examined in this session, including the use of signals of opportunity and the integration of inertial measurement units with laser scanners, magnetometers, barometric pressure sensors, and terrain sensors.

2.1.2 Session 3: Sensors and Enabling Technologies

In this session recent developments in inertial sensor technologies were reviewed, and an overview of precise time transfer, and its importance in military applications, was presented.

2.1.3 Session 4: Simulation and Testing

Results of research in the areas of personal navigation, GPS signal characterization and testing of military integrated navigation systems were presented in this session. The importance of a proper simulation and testing environment was emphasized in the design, development and testing of integrated navigation systems.

2.1.4 Session 5: Military Systems and Applications

The papers in this session presented the critical role of robust and accurate navigation systems in allowing networked and collaborative operations, increasing situational awareness, improving personal navigation, and operating in GNSS denied environments.

2.1.5 Session 6: Robust GNSS Integration Techniques

In this session, the potential advantages of alternative integration algorithms and filtering techniques were discussed. Recent results of the application of these techniques in INS/GPS integration and in personal navigation were presented. The filtering and integration techniques presented included deep and ultra-tightly coupled integration, sigma-point Kalman filtering and particle filtering.

In summary, the need for low-cost, small, accurate and robust navigation systems drives the research efforts in inertial sensors, integration techniques and algorithm development. This Symposium was a step in promoting co-operative research and information exchange in these important areas.

2.2 THE LECTURE SERIES

The objective of the Lecture Series “Low-Cost Navigation Sensors and Integration Technology”, was to have senior NATO subject matter experts present the current state-of-the-art in low-cost navigation sensors and system integration technology. Through this Lecture Series, the NATO/PfP community was updated and provided with an understanding of the issues faced by today’s system designers. In addition to sensor technologies, the Lecture Series included information on algorithms and innovative techniques. The applications described navigation in difficult urban, indoor, and underground environments where typical GPS receivers do not function.

The first set of Lecture Series organized by the Sensors and Electronics Technology Panel were held in Madrid, Spain on 27-28 October 2008; Delft, The Netherlands on 30-31 October 2008; and in Farnborough, UK on 3-4 November 2008. The topics covered by this set of lectures focused on understanding INS and GPS technologies, followed by topics addressing alternative and innovative technologies:

- INS/GPS Technology Trends;
- Inertial Navigation Sensors;
- Strapdown System Computational Elements;
- Strapdown System Performance Analysis;
- INS/GPS Integration Architectures;
- INS/GPS Architecture Performance Comparisons;
- Inertial MEMS System Applications;

- Optically and Ladar-Aided Navigation for Difficult Environments; and
- Advanced Concepts Using Signals of Opportunity and Other Natural Techniques.

An additional lecture entitled "Multi Sensor and High Integrity Integration" was presented in the UK Farnborough location. Finally, the proceedings were concluded with a round table discussion.

The second set of Lecture Series was held in Rome, Italy on 19-20 March 2009; Munich, Germany on 23-24 March 2009; and Warsaw, Poland on 26-27 March 2009. Minor modifications to the topics listed above were made. The topics presented in this version of the series are listed below:

- INS/GPS Technology Trends;
- Inertial Navigation Sensors;
- Inertial MEMS System Applications;
- INS/GPS Integration Architectures;
- INS/GPS Architecture Performance Comparisons;
- Precise Kinematic Relative Positioning with a Stand-Alone Miniaturized L1 GPS Data Logger;
- Optically and Ladar-Aided Navigation for Difficult Environments; and
- Advanced Navigation Concepts Using Signals of Opportunity and Other Natural Techniques.

Because of the demonstrated high interest level in the Lecture Series and a formal request from four other countries, a third set of lectures will be presented in 2010 in the following cities: Ankara, Turkey; Prague, Czech Republic; Toulouse, France; and Lisbon, Portugal.

Venues were selected to maximize access by the NATO and PfP nations and by the end of 2010, the Lecture Series will have been delivered in 10 different NATO cities. The Lecture Series has been regarded as very successful by the NATO and PfP scientists and engineers in attendance.

The Lecture Series has been documented and is available as RTO Educational Notes, RTO-EN-SET-116, 2009 [3]. The abstracts from several of the papers are presented below.

"INS/GPS Technology Trends", by Dr. George T. Schmidt

This paper focuses on accuracy and other technology trends for inertial sensors, Global Positioning Systems (GPS), and integrated Inertial Navigation System (INS)/GPS systems, including considerations of interference, that will lead to better than 1 meter accuracy navigation systems of the future. For inertial sensors, trend-setting sensor technologies will be described. A vision of the inertial sensor instrument field and inertial systems for the future is given. Planned accuracy improvements for GPS are described. The trend toward deeply integrated INS/GPS is described, and the synergistic benefits are explored. Some examples of the effects of interference are described, and expected technology trends to improve system robustness are presented.

"Inertial Navigation Sensors", by Dr. Neil M. Barbour

For many navigation applications, improved accuracy/performance is not necessarily the most important issue, but meeting performance at reduced cost and size is. In particular, small navigation sensor size allows the introduction of guidance, navigation, and control into applications previously considered out of reach

(e.g., artillery shells, guided bullets). Three major technologies have enabled advances in military and commercial capabilities: Ring Laser Gyros (RLGs), Fiber-Optic Gyros (FOGs), and Micro-Electro-Mechanical Systems (MEMS) gyros and accelerometers. RLGs and FOGs are now mature technologies, although there are still technology advances underway for FOGs. MEMS is still a very active development area. Technology developments in these fields are described with specific emphasis on MEMS sensor design and performance. Some aspects of performance drivers are mentioned as they relate to specific sensors. Finally, predictions are made of the future applications of the various sensor technologies.

"Computational Elements for Strapdown Systems", by Mr. Paul G. Savage

This paper provides an overview of the primary strapdown inertial system computational elements and their interrelationship. Using an aircraft type strapdown inertial navigation system as a representative example, the paper provides differential equations for attitude, velocity, position determination, associated integral solution functions, and representative algorithms for system computer implementation. For the inertial sensor errors, angular rate sensor and accelerometer analytical models are presented including associated compensation algorithms for correction in the system computer. Sensor compensation techniques are discussed for coning, sculling, scrolling computation algorithms and for accelerometer output adjustment for physical size effect separation and anisoinertia error. Navigation error parameters are described and related to errors in the system-computed attitude, velocity, and position solutions. Differential equations for the navigation error parameters are presented showing error parameter propagation in response to residual inertial sensor errors (following sensor compensation) and to errors in the gravity model used in the system computer.

"Performance Analysis of Strapdown Systems", by Mr. Paul G. Savage

This paper provides an overview of assorted analysis techniques associated with strapdown inertial navigation systems. The process of strapdown system algorithm validation is discussed. Closed-form analytical simulator drivers are described that can be used to exercise/validate various strapdown algorithm groups. Analytical methods are presented for analyzing the accuracy of strapdown attitude, velocity and position integration algorithms (including position algorithm folding effects) as a function of algorithm repetition rate and system vibration inputs. Included is a description of a simplified analytical model that can be used to translate system vibrations into inertial sensor inputs as a function of sensor assembly mounting imbalances. Strapdown system static drift and rotation test procedures/equations are described for determining strapdown sensor calibration coefficients. The paper reviews Kalman filter design and covariance analysis techniques and describes a general procedure for validating aided strapdown system Kalman filter configurations. Finally, the paper discusses the general process of system integration testing to verify that system functional operations are performed properly and accurately by all hardware, software and interface elements.

"INS/GPS Integration Architectures", by Dr. George T. Schmidt

An Inertial Navigation System (INS) exhibits relatively low noise from second to second, but tends to drift over time. Typical aircraft inertial navigation errors grow at rates between 1 and 10 nmi/h (1.8 to 18 km/h) of operation. In contrast, Global Positioning System (GPS) errors are relatively noisy from second to second, but exhibit no long-term drift. Using both of these systems is superior to using either alone. Integrating the information from each sensor results in a navigation system that operates like a drift-free INS. There are further benefits to be gained depending on the level at which the information is combined. This presentation will focus on integration architectures, including "loosely coupled", "tightly coupled", and "deeply integrated" configurations. The advantages and disadvantages of each level of integration will be listed. Examples of current and future systems will be cited. Examples of current and future systems will be cited.

"INS/GPS Architecture Performance Comparisons", by Dr. George T. Schmidt

Performance comparisons between the three major INS/GPS system architectures for various mission scenarios will be presented in order to understand the benefits of each. The loosely coupled and tightly coupled systems will be compared in several scenarios including aircraft flying against jammers and a helicopter flying a scout mission. The tightly coupled and deeply integrated architectures will be compared for several jamming scenarios including that of a precision guided munition.

"Inertial MEMS System Applications", by Dr. Neil M. Barbour

The performance of MEMS inertial technology has evolved from automotive quality to that approaching tactical-grade quality (1 deg/h, 1 mg). This evolution is a direct result of advances made in the key technology areas driven by gun-launched projectile requirements. The application of silicon MEMS inertial technology to competent munitions efforts began in the early 1990s. Initially, gun hardness was demonstrated at the sensor level, although the bias-and-scale factor of these gyros and accelerometers was mostly suitable for automotive or commercial use. Subsequently, development programs were initiated to develop gun-hard inertial systems with greatly improved sensor performance, and with a goal of low production cost. This paper discusses the evolution of low-cost MEMS inertial system technology development for guided projectile INS/GPS systems and high performance IMUs. The evolution in sensors and packaging to realize performance improvement and system size reduction are presented. Recent data from the culmination of a three-year effort to develop an 8 cu in IMU are summarized, and represent the highest performance to date for an all-silicon IMU. Further investments in gun-hard Silicon MEMS systems will ultimately realize IMUs that are smaller (less than 2 in^3 (33 cc), higher performing (1 deg/h and less than 1 mg), and lower in cost (less than $1200 per IMU and $1500 per INS/GPS) than is achievable in any competing technology.

"Navigating in Difficult Environments: Alternatives to GPS – 1", by Dr. Mikel M. Miller, Dr. Maarten Uijt de Haag, Dr. Andrey Soloviev and Dr. Michael Veth

This paper focuses on the latest technology trends for navigating in difficult urban, indoor, and underground environments where typical Global Positioning System (GPS) receivers do not function. The latest Alternative Navigation (Alt-Nav) technologies based on electro-optical techniques will be described. The Alt-Nav technologies presented include optically-aided Inertial Navigation Systems (INS) and Ladar-aided INS. Tightly integrating these technologies with an INS should lead to navigation performance similar to that achieved in today's GPS/INS integrations. An Alt-Nav integration vision for the future is given with some example configurations that improve overall navigation system robustness.

"Navigating in Difficult Environments: Alternatives to GPS – 2", by Dr. Mikel M. Miller, Dr. John F. Raquet and Dr. Maarten Uijt de Haag

This second paper focuses on additional novel technology trends for navigating in difficult urban, indoor, and underground environments where typical Global Positioning System (GPS) receivers do not function. The Alternative Navigation (Alt-Nav) technologies presented in this paper are based on RF Signals Of Opportunity (SoOP) and Biologically inspired Navigation (Bio-Nav). SOOP takes advantage of existing RF-signals to form a navigation solution while Bio-Nav seeks to understand and exploit methods used by animals and insects to navigate. Integrating these technologies with an INS should lead to navigation performance similar to that achieved in today's GPS/INS integrations. An additional Alt-Nav integration vision for the future is given using these techniques with some example configurations that improve overall navigation system robustness.

2.3 THE HANDBOOK

A previous RTO handbook, published in 2004 and entitled "Basic Guide to Advanced Navigation", SET-054/RTG-30 [6], focused on inertial and satellite navigation systems. While these are the common forms of navigation technology available today, and are expected to remain so in the foreseeable future, there are many applications for which traditional INS/GPS systems are not well suited. Thus, in May 2009, the group published a second edition to the first highly successful handbook. The newest handbook, "Basic Guide to Advanced Navigation, 2nd Edition" [4], reviews GPS and inertial navigation but, unlike the previous handbook, also highlights other technologies such as lesser known radio navigation aids, non-traditional sensors like pedometers and television signal receivers, innovative bio-inspired navigation concepts, and multi-sensor integration techniques.

The purpose of this handbook is to provide the reader an overview of various forms of navigation technologies currently or soon to be available, that have particular suitability in environments where traditional satellite navigation signals (such as GPS) may not be available, or where traditional inertial navigation systems may not be feasible due to physical or economical constraints. These can include urban, indoor, subterranean and other difficult and complex environments in which our forces are asked to operate.

The handbook is intended to familiarize NATO decision makers with the basic, but modern, navigation system technologies used in military guidance and navigation systems and describes projected technology advances recognized by the RTG members. The purpose of navigation is no longer confined to the classical problem of getting from point A to B on a defined route. Other critical requirements have emerged such as the necessity of command and control and situational awareness in the future networked collaborative battle space.

The updated handbook, replete with numerous graphs, tables and illustrations meets this need with a concise, readily understandable document. It concludes with a forecast that in the future every mobile entity in the battle space will have a positioning and navigation system. The capability provided will enable many advanced concepts such as collaborative engagement, asset tracking and weapons direction.

Chapter 3 – ADVANCES IN NAVIGATION SENSOR TECHNOLOGY

Numerous navigation sensor technologies that are or will be available for use in future military applications are summarized in Table 3-1. Each of these technologies is described in the subsequent sections. The table shows a number of relative qualities of each of the technologies, ranked on a scale of 1 to 3 (with 3 being best). The qualities rated in the table are:

- Application accuracy (Is the technology suitable for applications demanding high accuracy?);
- Cost;
- Autonomy/completeness (How much of the complete navigation solution does the technology provide?);
- Vulnerability (Is the technology reliant on an outside infrastructure that is vulnerable to interruption?); and
- Maturity (How mature is the technology in each of three time frames: 2010, 2015 and 2020?).

For example, an inertial navigation system consisting of medium-grade spinning mass gyro technology is suitable for medium accuracy requirements, is of moderate cost, is completely self-contained (provides the entire navigation solution), does not rely on outside infrastructure, and is highly mature.

Table 3-1: Sensor Technologies.

	Sensor Technology	**Application Accuracy**[1]	**Cost**[1]	**Autonomy/ Completeness**[1]	**Vulnerability**[1]	**Maturity**[1]		
						2010	2015	2020
Inertial Sensor Technologies	Spinning Mass (Low grade)	1	3	3	3	3	3	1
	Spinning Mass (Med. grade)	2	2	3	3	3	3	1
	Spinning Mass (High grade)	3	1	3	3	3	3	3
	RLG (Low grade)	1	3	3	3	3	3	3
	RLG (Med. grade)	2	2	3	3	3	3	3
	FOG (Low grade)	1	3	3	3	3	3	3
	FOG (Med. grade)	2	3	3	3	3	3	3
	FOG (High grade)	3	2	3	3	2	3	3
	MEMS (Low grade)	1	3	3	3	3	3	3
	MEMS (Med. grade)	2	2	3	3	2	2	3

	Sensor Technology	Application Accuracy[1]	Cost[1]	Autonomy/ Completeness[1]	Vulnerability[1]	Maturity[1]		
						2010	2015	2020
	MOEMS	2	3	3	3	1	1	2
	Vibrating (Low grade)	1	3	3	3	3	3	3
	Vibrating (Med. grade)	2	2	3	3	2	3	3
	Ultra-Cold Atom	3	1	3	3	1	1	1
Velocity and Distance Travelled Sensors	Speed Sensors (odometer, air/ water speed, etc.)	1	3	1	3	3	3	3
	Pedometers	1	3	1	3	3	3	3
	Doppler Velocity Sensor	2	2	1	3	3	3	3
	Zero Velocity Update	3	0	1	3	3	3	3
	Visual Odometry	1 – 2	1	1	3	1	2	3
Heading Sensors	Magnetic Compass	1	3	1	3	3	3	3
	Gyrocompass	3	1	1	3	3	3	3
Altitude/ Depth Sensors	Barometric Altimeter	2	3	1	3	3	3	3
	Radar/Laser Altimeter	2	2	1	2	3	3	3
	Water Depth	3	3	1	3	3	3	3
Time of Arrival / Time Difference of Arrival (Range determination)	LORAN-C	2	3	3	2	3	?	1
	eLoran	3	3	3	2	1	2	3
	Distance Measuring Equipment (DME)	1	3	2	2	3	3	1
	Pseudolites	3	2	2	1	2	3	3
	Ultra-Wideband	2	3	3	2	2	3	3

	Sensor Technology	Application Accuracy[1]	Cost[1]	Autonomy/ Completeness[1]	Vulnerability[1]	Maturity[1]		
						2010	2015	2020
Angle (Bearing Determination)	VHF Omni Directional Radio-range (VOR)	1	3	2	2	3	3	1
	TACAN	1	3	2	2	3	3	1
Signals of Opportunity	Radio/TV Broadcast Signals	1	3	3	2	1	2	3
	Mobile Telephone Positioning	1	3	3	2	2	3	3
	Signal Strength	1	3	3	2	2	3	3
Satellite Navigation Systems	GPS	3	3	3	1	3	3	3
	Glonass	3	3	3	1	2	3	3
	Galileo	3	3	3	1	1	3	3
	Compass	3	3	3	1	1	3	3
	IRNS/QZSS	3	3	3	1	1	2	3
	GPS Augmentations	3	3	1	1	3	3	3
Database Matching	Map Matching	2	2	3	2	3	3	3
	Image Matching	2	2	3	2	2	3	3
	Laser Imaging	3	2	3	2	2	3	3
	Terrain Referenced Navigation	2	2	3	2	3	3	3
	Celestial Navigation	2	1	1	3	3	3	3
	Gravimetry	1	1	1	3	2	3	3
Bio-Inspired Navigation	Light Polarization	1	2	1	3	1	2	2
	Landmark	2	3	3	3	3	3	3
	Magnetic	1	3	1	3	3	3	3
	Echo	3	3	1	2	3	3	3
	Olfactory	1	2	1	2	1	2	2

[1]Notes:

Application Accuracies	Cost:	Autonomy:	Vulnerability:	Maturity Levels:
1 = Tactical (Low)	1 = High	1= Low	1 = High	1 = Experimental or Obsolete
2 = Navigation (Medium)	2 = Medium	2 = Medium	2 = Medium	2 = Developmental
3 = Strategic (High)	3 = Low	3 = High	3 = Low	3 = Operational

3.1 INERTIAL SENSOR TECHNOLOGIES

The basic sensors within an Inertial Navigation System are accelerometers (to measure linear motions) and gyroscopes (to measure rotational motion).

Accelerometers fall into two main categories:

- Pendulous rebalanced accelerometers; and
- Vibrating beam accelerometers.

Gyroscopes are more diverse:

- Earlier designs consisted of metal wheels spinning in ball or gas bearings;
- Optical gyros have counter-rotating laser beams either in an evacuated cavity (RLG: Ring Laser Gyro) or in an optical fibre (FOG: Fibre-Optic Gyro); and
- Other designs use resonators (vibrating elements) of different shapes (e.g., bars, cylinders, rings and hemispheres) and are known under the generic name of Coriolis vibrating gyros.

Both accelerometers and gyros are generally moving from older construction methods consisting of assembling large numbers of mechanical parts, to modern automatic mass production techniques. One such technique uses Micro-Electro-Mechanical Systems (MEMS) technology, micro-machined from silicon or quartz, which enables true solid state sensors. MEMS or Optical MEMS (MOEMS) technologies offer a complete sensor and supporting electronics on a single integrated circuit chip.

Active research in new technologies is continuing; future designs exploiting the properties of individual atoms may provide breakthroughs in inertial sensing performance.

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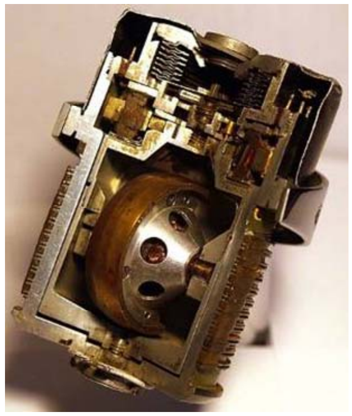

Northrop Grumman

Draper/ Honeywell

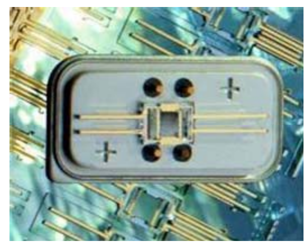

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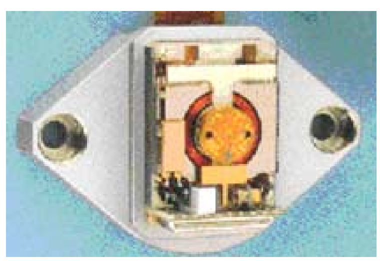
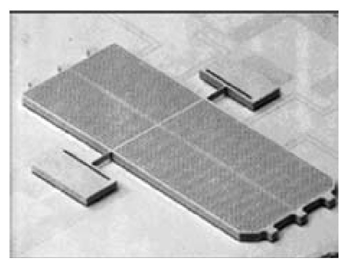
Figure 3-1: Gyroscope Types (clockwise from top left): Spinning Mass, Ring Laser Gyro, Tuning Fork Resonator, MEMS Vibratory Gyro.

BAE Systems





Draper

Figure 3-2: Accelerometer Types (left to right): Pendulous Rebalanced, MEMS Vibratory Accelerometers.

For the interested reader, more detailed information about inertial sensor components was presented in both the final report (Ref. [1]) and the handbook (Ref. [6]) produced by the previous group. References [3], [7], [8] and [9] are also useful resources.

3.2 VELOCITY AND DISTANCE TRAVELLED SENSORS

There are a number of sensors available to measure speed, velocity and distance travelled to varying degrees of accuracy. When coupled with other sensors such as heading determination systems, they can form a dead reckoning navigation system. When used as an aid to an inertial navigation system they provide error growth control.

Examples of such devices include odometers, pedometers, Doppler velocity sensors, air speed sensors, water speed logs, visual odometry systems, zero-velocity updates, etc. Some of these, such as pedometers, are especially applicable to urban, indoor and subterranean environments.

3.2.1 Speed Sensors

Land, air and water speed sensors, although mechanically different, all provide similar information: the speed of the user relative to the surrounding environment. These sensors tend to be very reliable and inexpensive; however their measurement errors are environmentally dependent and must be calibrated for accurate applications.

In land vehicles, odometers, often called Vehicle Motion Sensors (VMS), measure the number of wheel, engine or transmission rotations. The number of rotations multiplied by the wheel circumference provides the distance travelled, and the rotation rate provides the speed.

An air speed indicator uses a pitot tube to measure the difference between the static pressure and the total pressure. This difference is related to the speed of the air vehicle with respect to the air.

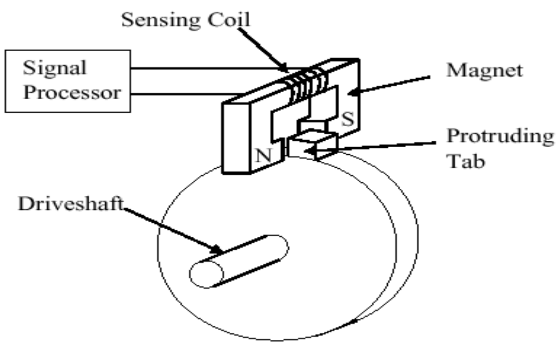


Figure 3-3: Odometer.

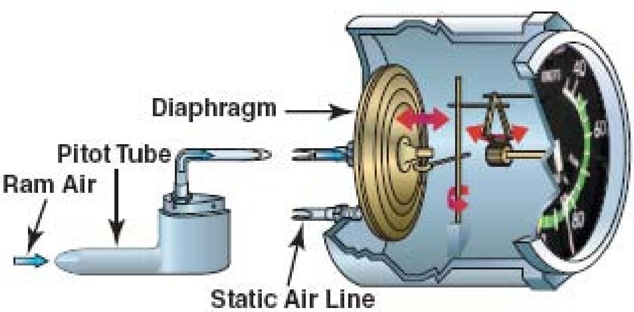


Figure 3-4: Air Speed Indicator.

Water speeds can be measured with an Electromagnetic (EM) speed log. An EM log generates an electromagnetic flux that changes with the speed of water flowing over it providing the relative speed of the vehicle with respect to the water. Water speed can also be measured with a mechanical speed log: the flow of water over a propeller causes it to rotate. The number of revolutions of the propeller per unit time is proportional to the speed of the vehicle with respect to the water.

3.2.2 Pedometers

A pedometer is a small device, usually containing a simple accelerometer, which counts the steps a user makes to determine distance travelled. Pedometers are inexpensive, lightweight, passive, self contained and readily available. However, because of variations in the length of a stride, errors are typically on the order of 10% of the distance travelled. As part of an integrated system, the calibration of the user's stride length can be done when more accurate independent sensors are available (e.g., GPS).

Figure 3-5: Pedometers work well for uniform-stride pedestrian navigation systems, but may not perform so well for soldier movements such as crawling, sidestepping and walking backwards.

3.2.3 Doppler Velocity Sensor

A Doppler radar velocity sensor is a device that transmits and receives a low power radio signal, and deduces its velocity based on the shift in frequency of the returned signal as it reflects from nearby objects. This shift in frequency is known as the Doppler effect, and is directly related to the velocity (speed and direction) of the sensor.

Doppler radar systems are available commercially for automotive and traffic enforcement applications and are being adapted to personal navigation systems. These sensors provide very accurate user velocity; however they are not covert and the measured velocity is sensitive to user orientation.

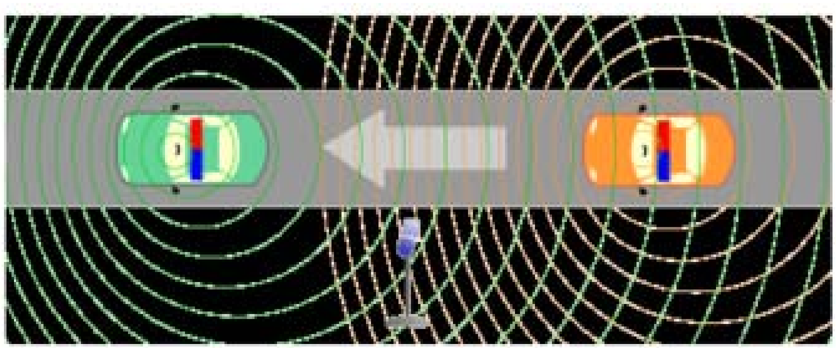


Figure 3-6: The Doppler Effect (the velocity of a moving transmitter is directly related to the shift in frequency observed).

Figure 3-7: The DRS1000 Doppler Radar Speed Sensor from GMH Engineering.

For marine vehicles, a Doppler Velocity Log (DVL) sends acoustic beams and uses the Doppler effect to measure the speed of the vehicle with respect to sea floor. However, this system is limited to about 200 m depths and suitably reflective sea floor conditions.

3.2.4 Zero Velocity Update

Zero Velocity Updates (ZVU), or measurements of velocity = 0, are most often used to control the error growth in Inertial Navigation Systems (INS). A ZVU can be made whenever a user, such as a land vehicle or a dismounted soldier, is known to be stationary. The concept is simple: when the INS is stationary, its known velocity (zero) can be used as a measurement to update the navigation processing filter. ZVUs can be processed continually as long as the INS is stationary. They may be scheduled, requiring the operator to hold stationary for a short length of time. Additionally, periods of zero motion can be automatically detected by software and a ZVU executed.

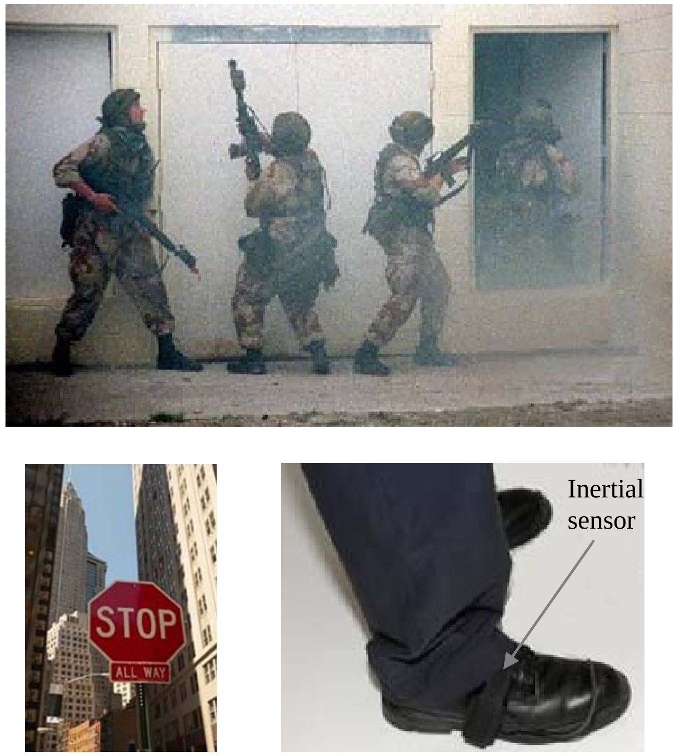


Figure 3-8: ZVUs can be performed when vehicles are stopped, when soldiers are relatively stationary, or even on every footfall of a foot-mounted sensor.

3.2.5 Visual Odometry

Visual odometry ([10], [11]) refers to the estimation of relative platform motion from visual data. The determination of motion parameters starts with establishing feature correspondences between consecutive image frames, either by feature tracking or feature matching. Distinctive image points and straight line segments are examples of commonly used image features. Assuming a static scene, motion parameters, such as velocity or distance travelled, can be accurately estimated through the application of geometrical constraints.

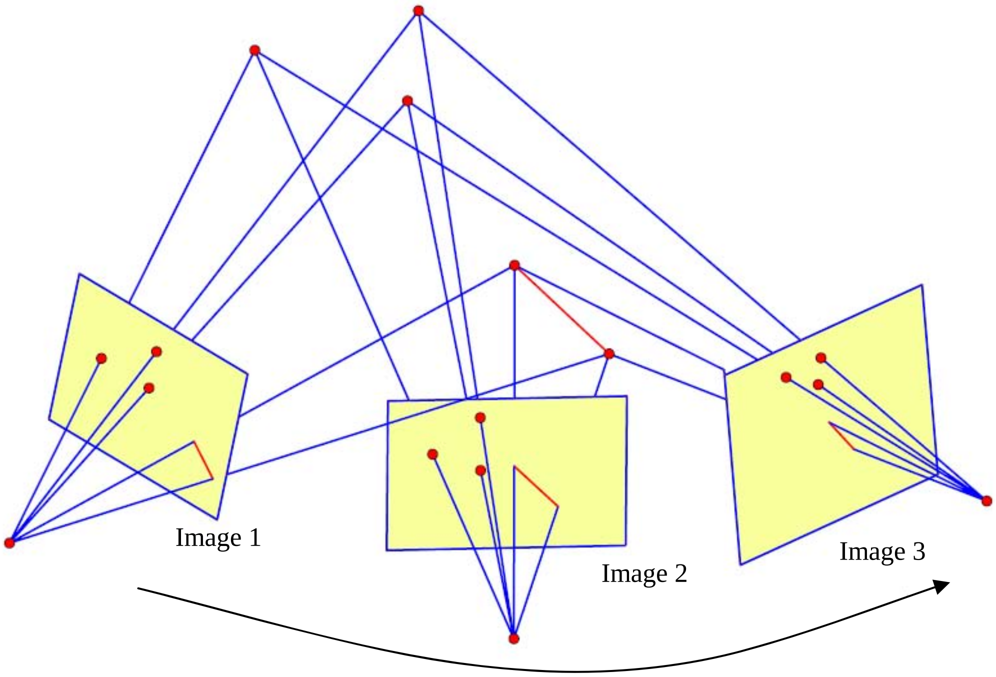


Figure 3-9: Estimating Camera Motion by the 3D Mapping of Points and Line Segments from Multiple Images of an Image Sequence.

Features extracted from sequences of images can be used to provide position and attitude updates to an INS through an extended Kalman filter (Chapter 4). This is referred to as Image-Aided inertial navigation.

In addition to the navigation solution, the visual approach offers the opportunity to construct a sparse map of the environment. This exploration technique is closely related to what is known in the robotics community as *Simultaneous Localization And Mapping* (SLAM). These maps can potentially be used for map-matching (Section 3.9.1).

Image processing algorithms can be applied to estimate absolute position coordinates if a geo-referenced image database is available for matching. Similar techniques can be used with other sensors such as radar, laser radar (LIDAR/LADAR) or thermal imaging cameras.

3.3 HEADING SENSORS

This section presents the common sensors used to indicate a platform's heading with respect to North (azimuth). They are commonly found on ships and airplanes and, when integrated properly, provide information for navigation, pointing or precise target localization.

3.3.1 Magnetic Compass

Magnetic sensors determine heading by sensing the intensity and inclination of the Earth's magnetic field. However, local disturbances in the Earth's magnetic field caused by nearby permanent magnets, electric currents, or large iron bodies can dramatically affect the derived azimuth, or even prevent their use. The azimuth

angles from magnetic compasses must be corrected for magnetic declination if they are to refer to true north. Magnetic declination, or the difference between magnetic north and true north, varies with position and time.

The sensors are passive, self-contained, of very small size, low cost, and lightweight. The accuracy of derived azimuths from magnetic compasses depends heavily on the degree to which the local magnetic field is being disturbed. When properly calibrated, heading accuracy can be on the order of 1 degree.

Figure 3-10: A Digital Magnetic Compass from KVH Industries.

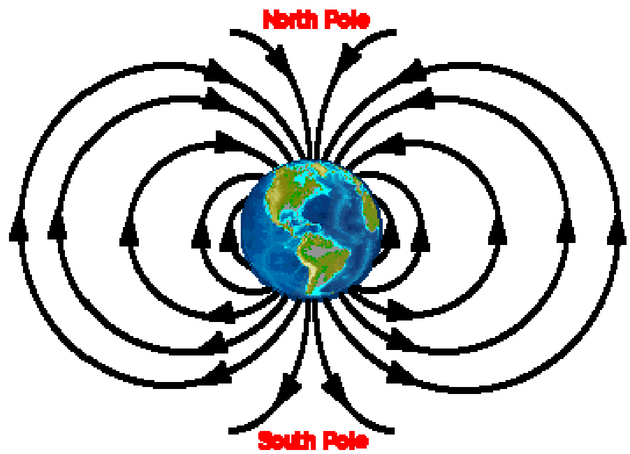


Figure 3-11: Earth's Magnetic Field.

3.3.2 Gyrocompass

Gyrocompasses use gyroscopic technologies, as described earlier in Section 3.1, to determine the direction of the Earth's rotational axis, i.e., true north.

Gyrocompasses measure the Earth's rotation rate (15 degrees/hour) in the horizontal plane. A measurement of zero indicates east while the maximum measurement (Earth's rotation rate times cosine(latitude)) indicates north.

They have two main advantages over magnetic compasses: they find true north, i.e., the direction of Earth's rotational axis (as opposed to magnetic north), and they are not susceptible to external magnetic fields.

For applications such as artillery pointing (which generally requires pointing accuracies of 1/1000 of a radian), gyrocompasses need to be able to sense rotations to accuracies on the order of 1/1000 of the horizontal component of Earth's rotation rate (0.01 deg/hr at 45 degrees latitude).

In the case of a gyrocompass using medium performance class fiber-optic gyros, the heading accuracy is better than 0.5 degrees and can be used as a ship's main navigation instrument.

Figure 3-12: Cutaway of an Early Anschütz Gyrocompass (Wikipedia Commons Image).

Figure 3-13: A Modern Fibre-Optic Gyrocompass (IXSEA OCTANS).

3.4 ALTITUDE/DEPTH SENSORS

Many navigation systems do not provide very good indications of height or depth. Inertial systems are unstable in the vertical axis and if unaided will provide no useful height information. Dead reckoning by compass and distance travelled provides no height information at all. In difficult urban, subterranean, or underwater environments, the knowledge of height (or depth) is often critical to mission success. A few applicable sensor technologies that measure height/depth are outlined below.

3.4.1 Barometric Altimeter

Barometric altimeters provide a measure of altitude based on the measure of static atmospheric pressure. This pressure measurement is directly related to the height above mean sea level. Like many speed sensors, they tend to be very reliable and inexpensive. However, the pressure readings vary with weather conditions and must be corrected on a regular basis with a reference barometric altimeter at a known height and nearby location for long duration applications.

Figure 3-14: Druck Barometric Altimeters.

3.4.2 Radar Altimeter

For airborne applications, radar altimeters can be used to provide a very accurate measure of the height of the platform above the ground level. A low power radio signal is transmitted towards the ground, and the time required for the signal to reflect from the surface and return to the altimeter provides a direct measure of height above ground. Miniature radar altimeters that would be of use in micro air vehicle applications are available that can measure the height above the ground to a few centimetres.

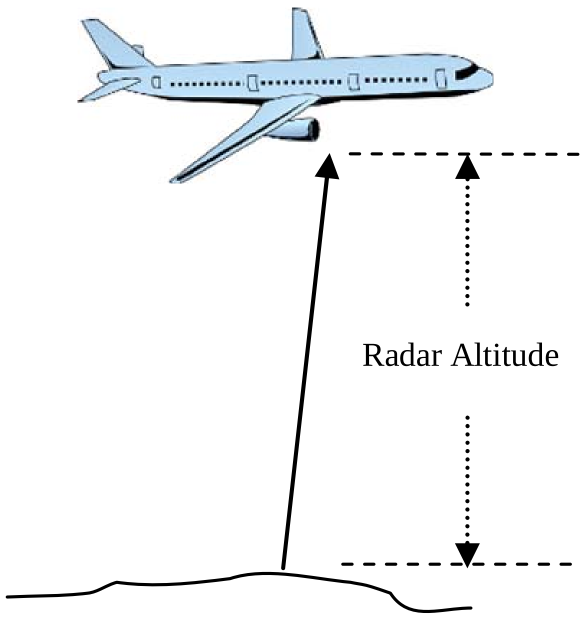


Figure 3-15: Radar Altimeter Concept.

3.4.3 Water Depth

Used in underwater vehicles, depth sensors typically measure water pressure. A precision quartz crystal resonator whose frequency of oscillation varies with pressure-induced stress is thermally compensated to calculate depth and can achieve high accuracy over a broad range of temperatures. Accuracies on the order of 0.01% can be achieved.

Figure 3-16: Depth Sensors from Digiquartz Technologies.

3.5 TIME OF ARRIVAL / TIME DIFFERENCE OF ARRIVAL (RANGE DETERMINATION)

The use of radio waves to obtain a navigation solution relies on the propagation speed of light. Given the known speed of light, the range between a radio transmitter and receiver can be calculated given the time taken for the signals to travel between them. Propagation uncertainties can significantly affect achievable ranging accuracies.

In a Time Of Arrival (TOA) system, position is derived by computing the distance from the receiver to each transmitter, by measuring the time taken for a signal to travel from the known transmitter's location to the receiver. The receiver requires a clock synchronised with the transmitters.

In a Time Difference Of Arrival (TDOA) system, pairs of stations transmit simultaneous pulses which arrive at the user's location with a small time difference. A single time difference represents a hyperbolic Line Of Position (LOP). The intersection of two or more hyperbolic LOPs defines the receiver's position. The receiver does not require a clock in this case.

3.5.1 Global Navigation Satellite System (GNSS)

A GNSS receiver uses timing signals from a constellation of orbiting satellites to determine its geographic location using range measurements from four or more satellites with precisely known locations.

There are four GNSS currently operating or in development: the US Global Positioning System (GPS), the Russian Global Navigation System (GLONASS), the European Union GALILEO, and the Chinese COMPASS system. These systems are designed to give three-dimensional position, velocity and time data almost anywhere in the world with an accuracy of a few meters.

For a more detailed description of the operation of GNSS see Section 3.8.

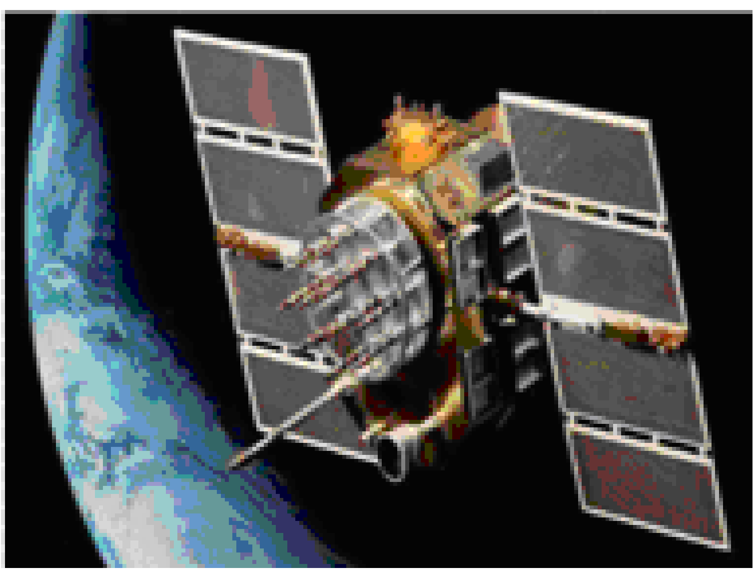


Figure 3-17: A GPS Satellite.

3.5.2 Loran-C

Loran-C (LOng RAnge Navigation) is a Time Difference Of Arrival (TDOA), low-frequency navigation and timing system originally designed for ship and aircraft navigation.

A Loran receiver measures the time difference of arrival between pulses from pairs of stations. This time difference measurement places the receiver somewhere along a hyperbolic Line Of Position (LOP). The intersection of two or more hyperbolic LOPs, provided by two or more time difference measurements, defines the receiver's position. Accuracies of 150 to 300 m are typical.

Loran-C has a number of advantages: it uses a very strong transmitted signal which is difficult to jam, it can sometimes be an independent backup to GPS, it provides for high accuracy time dissemination, and the low frequency signal penetrates indoors much better than GPS. However, the positioning accuracy of Loran-C alone is not sufficient for urban/indoor use. There is no global coverage, and the system as a whole has an uncertain future.

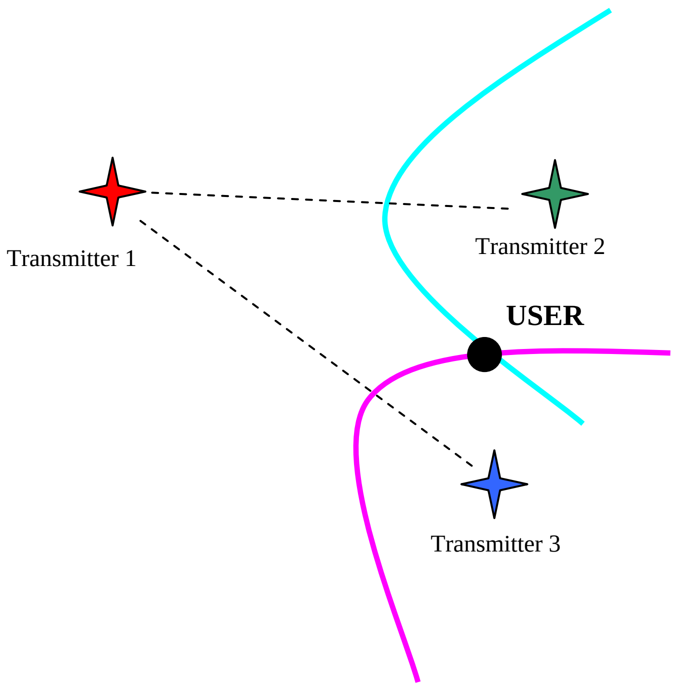


Figure 3-18: A Loran-C user position is at the intersection of hyperbolic lines of position which result from the time difference of arrival of pulses from pairs of transmitter stations (1 & 2 and 1 & 3).

3.5.3 eLoran

Enhanced Loran, or eLoran, is an international initiative underway to upgrade the traditional Loran-C system for modern applications. The infrastructure is now being installed in the US, and a variation of eLoran is already operational in northwest Europe.

eLoran receivers employ Time Of Arrival (TOA) positioning techniques, similar to those used in satellite navigation systems. They track the signals of many Loran stations at the same time and use them to make

accurate and reliable position and timing measurements. It is now possible to obtain absolute accuracies of 8 – 20 m and recover time to 50 ns with new low-cost receivers in areas served by eLoran.

Also significant is the addition of a data channel which allows eLoran to meet the accuracy and integrity requirements of ship harbour entrance and aircraft non-precision approach. The data channel broadcasts differential corrections, warnings, and signal integrity information to the user's receiver.

Figure 3-19: A Combined GPS/eLoran Receiver and Antenna from Reelektronika.

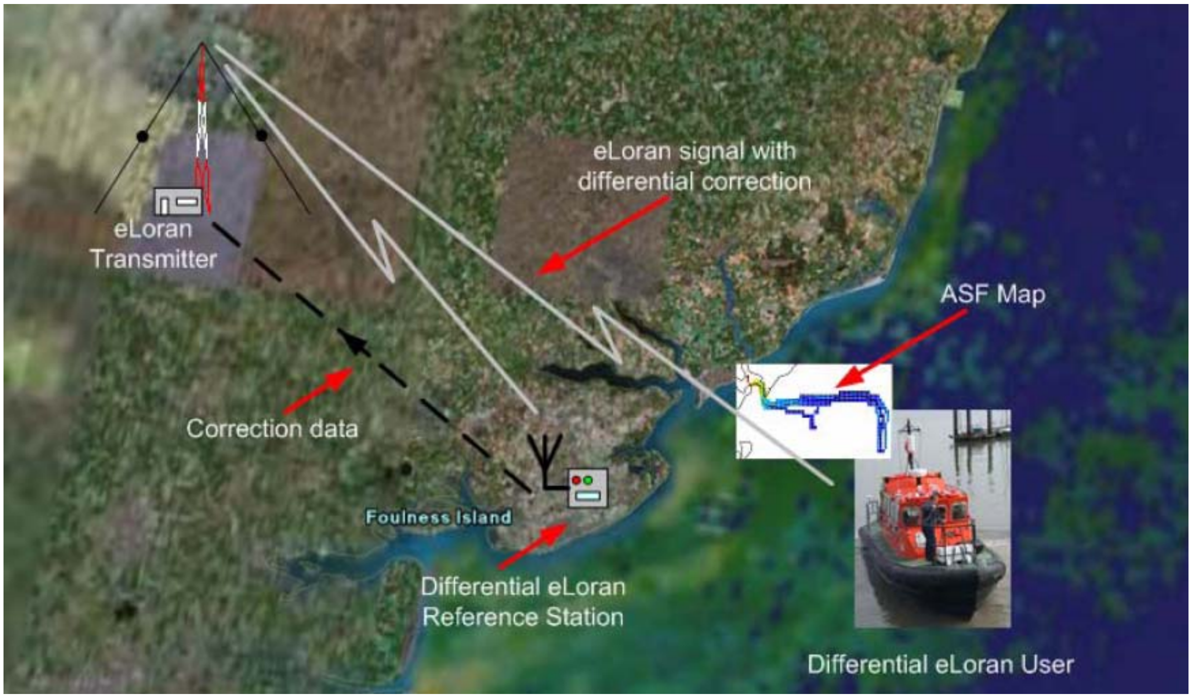


Figure 3-20: The Differential eLoran Concept (G. Offermans, 2007).

3.5.4 Distance Measuring Equipment (DME)

Distance Measuring Equipment (DME) stations for aircraft navigation were developed in the late 1950s and are still in world-wide use as a primary navigation aid. The DME ground station receives a signal from the user and transmits it back. The user's receiving equipment measures the total round trip time for the interrogation/ reply sequence, which is then halved and converted into a slant range between the user aircraft and the DME station.

There are no plans to improve the DME network, though it is forecast to remain in service for many years. Over time the system will be relegated to a secondary role as a backup to GNSS-based navigation.

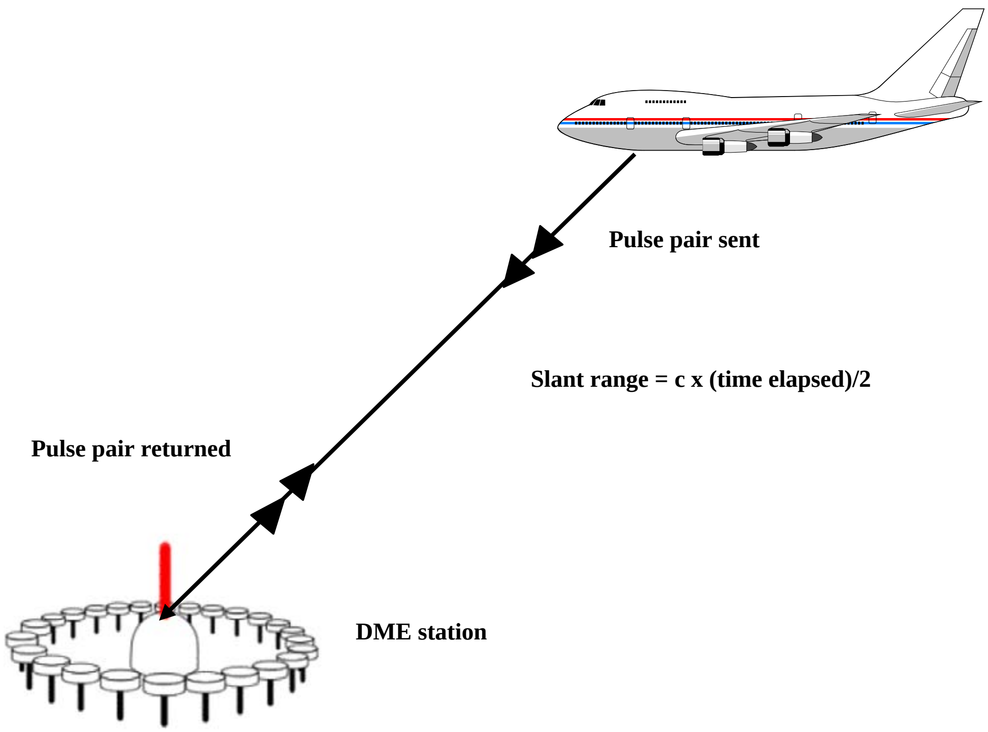


Figure 3-21: Aircraft DME (Distance Measuring Equipment) Range Determination System.

3.5.5 Pseudolites

A pseudolite (pseudo-satellite) is a ground-based transmitter that is capable of transmitting navigation signals that mimic satellite navigation systems. They can be used to augment GNSS satellite signals where there may be significant satellite shading effects, such as indoors.

In order to utilize pseudolites with a GNSS, the signals must be time synchronized with GNSS time, the location of the pseudolites must be known, and the transmitted signals must be of compatible power levels.

If one assumes that the receiver uses **only** pseudolite signals, the transmitted signal power can be changed at will to penetrate difficult environments. For best performance, the pseudolites should be placed around the area of interest to provide good geometry, and therefore good accuracy.

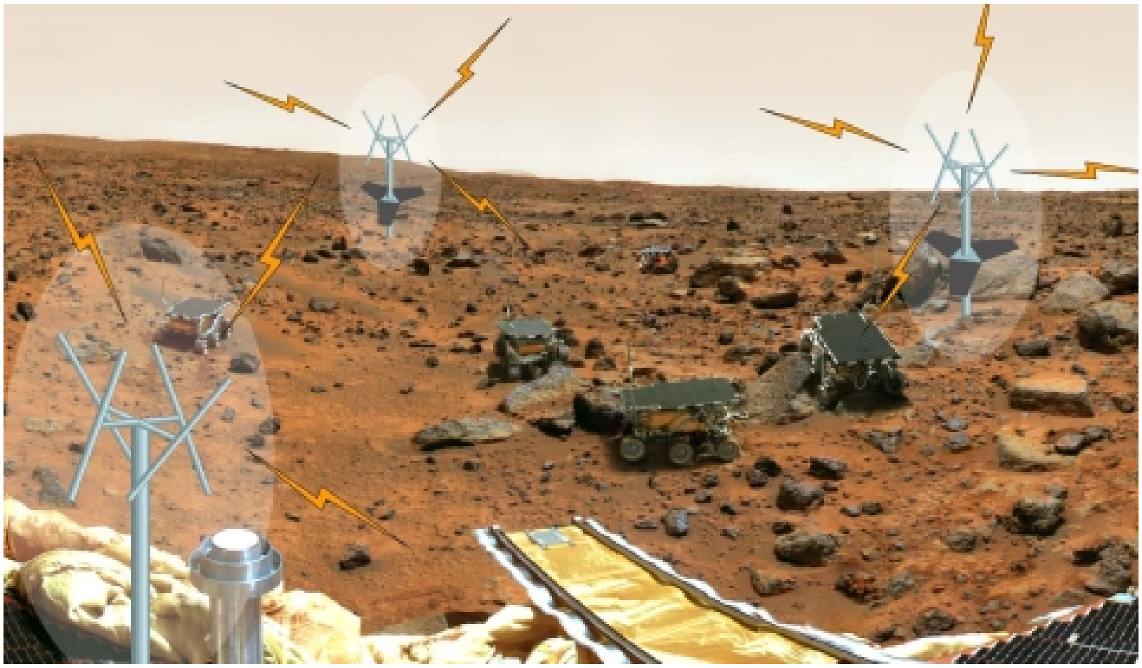


Figure 3-22: Ground-Based Pseudolites Deployed for a Conceptual Mars Mission (LeMaster 2001).

3.5.6 Ultra-Wideband

Ultra-Wideband (UWB) signals are produced by generating and transmitting short pulses of RF energy (on the order of nanoseconds and less). Such short pulse durations in the time domain result in a very wide bandwidth in the frequency domain. Because of this short pulse duration, very high range resolution is possible. Positioning with UWB technology is accomplished by measuring the Time Of Arrival (TOA) or Time Difference Of Arrival (TDOA) of the UWB signals. For example, a number of beacons at known positions transmit pulses synchronously and the receiver computes its position by TOA (similar to GPS) or TDOA (similar to Loran-C). A number of UWB systems have demonstrated indoor positioning with errors of less than 1 m. However, positioning accuracies will depend on the geometry of the beacons and the obstacles between the transmitter and receiver.

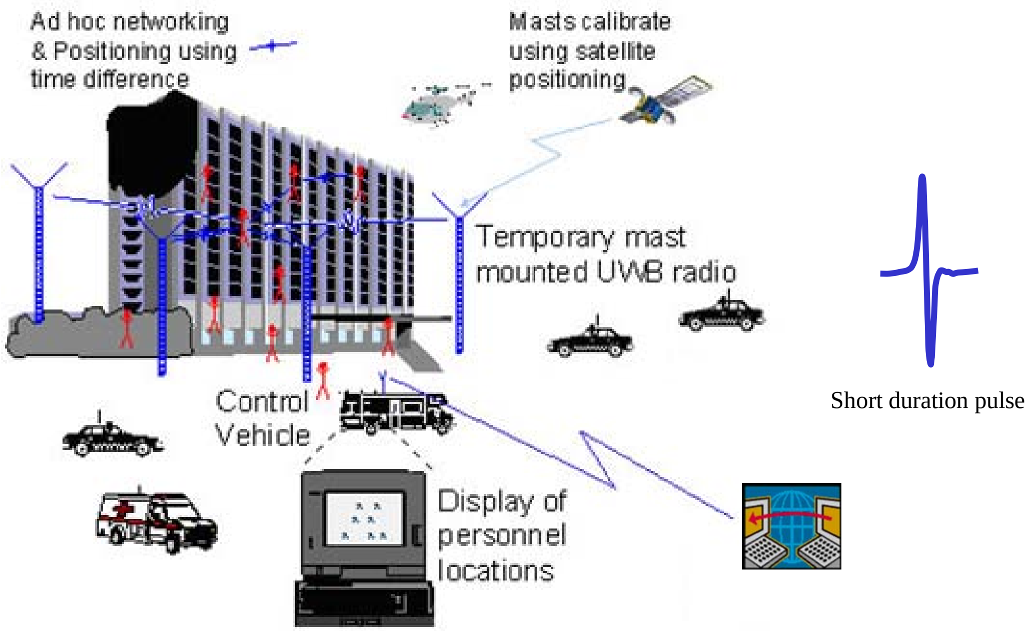


Figure 3-23: UWB Positioning Concept of Europcom (Emergency Ultra-Wideband Radio for Positioning and Communications, Delft University of Technology, et al.).

3.6 ANGLE (BEARING DETERMINATION)

A few radio navigation aids are based on angle or bearing determination from the user's receiver to a reference location. If angle observations to a sufficient number of geographically dispersed sites are made, the user's position can be triangulated. If there are insufficient observations for a position fix, such systems are still useful as heading determination or homing systems, or can be used in a larger integrated system coupled with information from other sensors. Examples of bearing determination systems for aircraft include VOR (VHF Omni Directional Radio-range) and TACAN (Tactical Air Navigation) systems.

3.6.1 VHF Omni Directional Radio-Range (VOR) System

The VHF Omni Directional Radio-range (VOR) system is comprised of a series of ground-based beacons operating in the VHF band (108 to 118 MHz). A VOR station transmits a reference carrier Frequency Modulated (FM) with a 30 Hz signal from the main antenna. An Amplitude Modulated (AM) carrier is electrically swept around several smaller antennas surrounding the main antenna. This rotating pattern creates a 30 Hz Doppler effect on the receiver. The phase difference of the two 30 Hz signals gives the user's azimuth with respect to the North from the VOR site.

The bearing measurement accuracy of a VOR system is typically on the order of 2 degrees, with a range that extends from 25 to 130 miles.

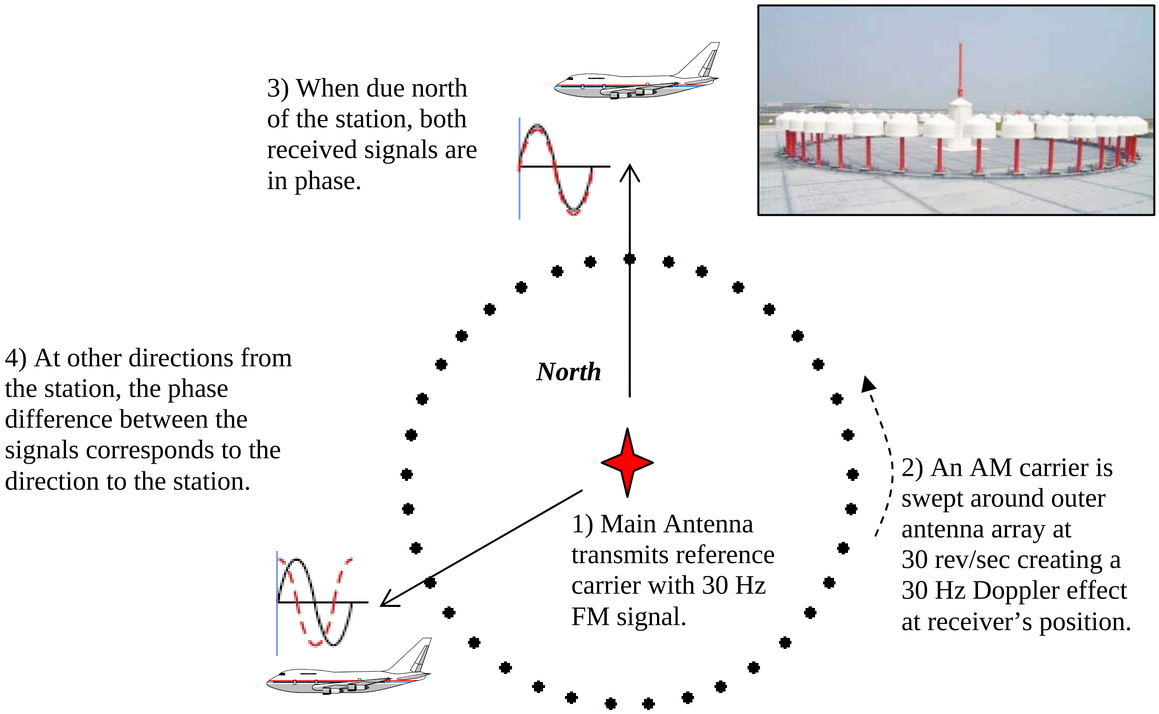


Figure 3-24: Determining Bearing to a VOR Station.

3.6.2 TACAN

TACAN (Tactical Air Navigation) is an enhanced VOR/DME system designed for military applications. The VOR component of TACAN, which operates in the UHF spectrum, makes use of a two-frequency principle, enabling higher bearing accuracies. The DME (Section 3.5.4) component of TACAN operates with the same specifications as civil DME.

The accuracy of the azimuth component is about ±1 degree, while the accuracy of the DME portion is ±0.1 nautical miles. For military usage a primary drawback is the lack of radio silence caused by aircraft DME transmissions.

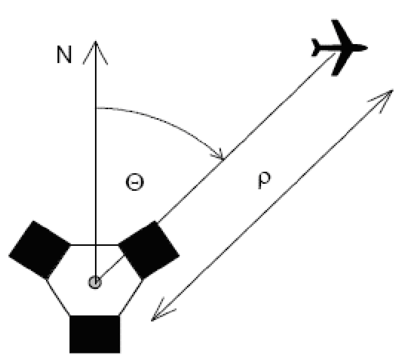
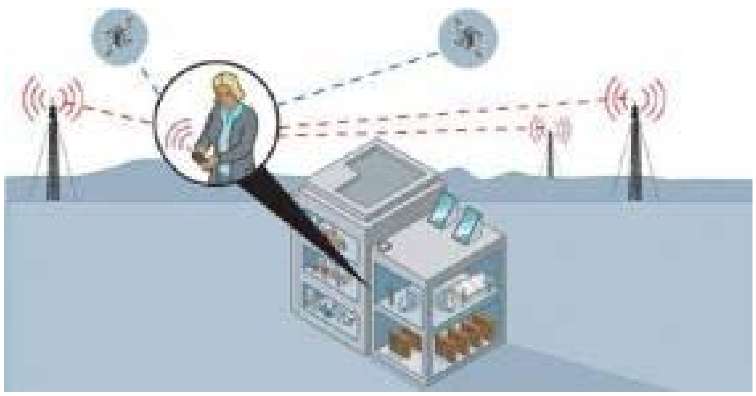


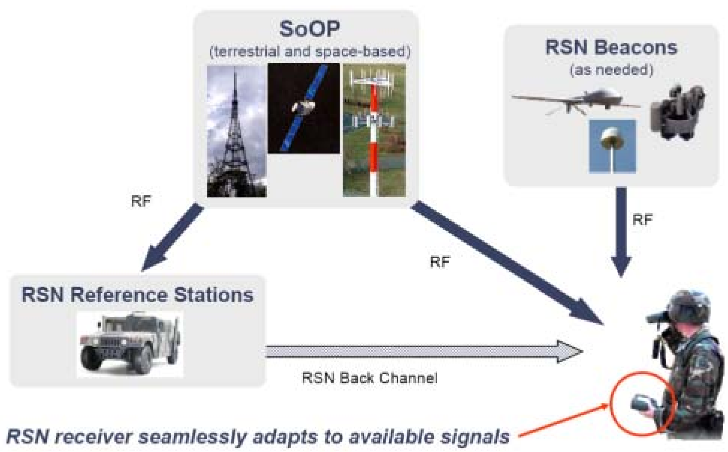
Figure 3-25: TACAN is the Military Enhancement of VOR/DME.

3.7 SIGNALS OF OPPORTUNITY

Recent research efforts are seeking ways to develop technology capable of determining one's position on the Earth based on any or all available "signals of opportunity" (cell phone towers, TV transmitters, etc.). By measuring the time it takes the signal to travel from the transmitter to the receiver, a range to the transmitter can be estimated. However, since signals of opportunity are not usually designed for navigation, a reference station is usually required to provide additional timing and reference data.



(Boeing)



(Argon ST)

Figure 3-26: The Robust Surface Navigation (RSN) program, being led by teams from Boeing and Argon ST, is currently studying the exploitation of such Signals of Opportunity (SoOP).

3.7.1 Radio/TV Broadcast Signals

The use of radio or TV broadcast signals can be used to provide a user's position. By measuring differences in the times at which the broadcast signals arrive at a user's location and at a second receiver at a known fixed location, an estimate of the ranges between the user and the transmitters can be determined.

The exploitation of such signals comes with several advantages. No deployment of a transmitter network is required (it is already available), and the high power, relatively low frequency signals penetrate buildings well and are less susceptible to multi-path. However, the concept can only be employed in areas in which there are known operating TV or radio broadcast stations.

For outdoor receivers, position accuracies of a few meters over baselines of several hundreds of meters have been demonstrated. However, positioning accuracy will depend on the geometric distribution of the broadcast stations with respect to the user's position.

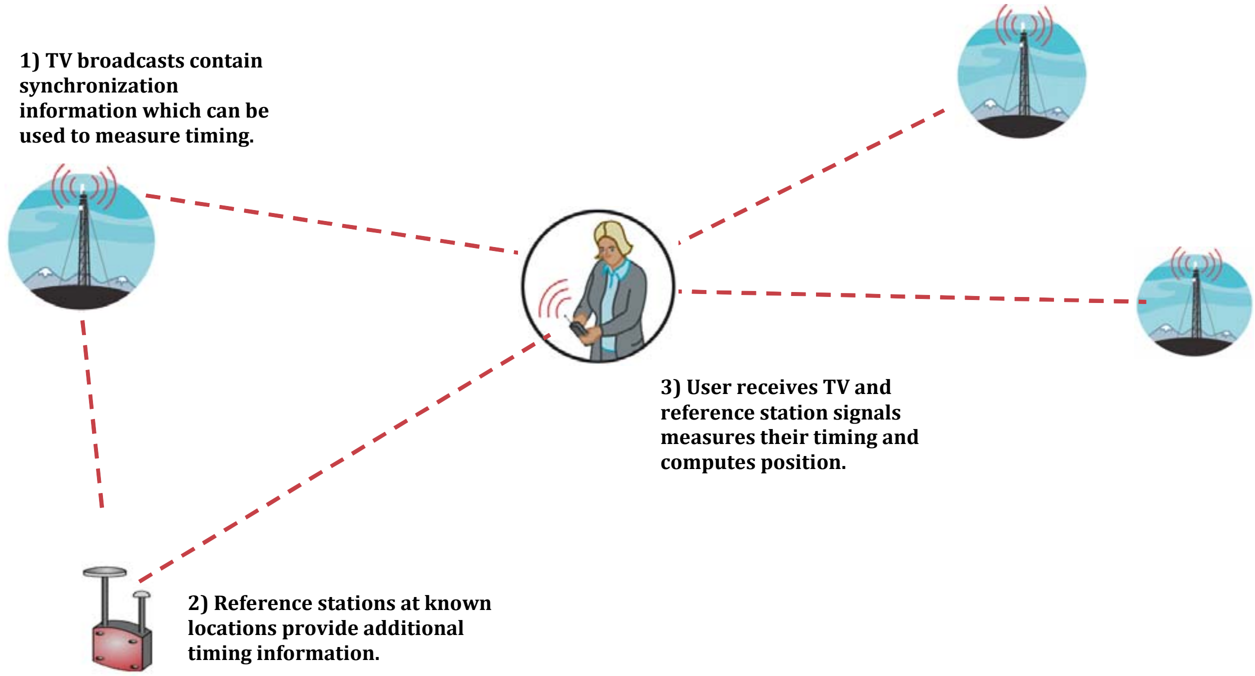


Figure 3-27: TV and radio station transmitters can be used for positioning (G. Duckworth, QinetiQ).

3.7.2 Mobile Telephone Positioning

Positioning information can be obtained from mobile telephone systems. Either the Time Difference Of Arrival (TDOA) or Time Of Arrival (TOA) of signals transmitted between the wireless handset and the network can be used. Position may then be estimated by intersections of lines of position. Positioning accuracies better than 50 m have been shown, given a proper geometry between the user's mobile handset and the transmit towers.

The main advantage of such systems is that a special transmitter for positioning purposes is not required. The mobile handset is a relatively low cost and ubiquitous commercial device.

The main disadvantage of telephone positioning systems is that the geometry of the base stations is optimized for communications, not positioning. As a result, the geometry may be very poor resulting in degraded accuracies on the order of 100 – 200 m. Also additional software/hardware may be required in the mobile phone network and/or handset.

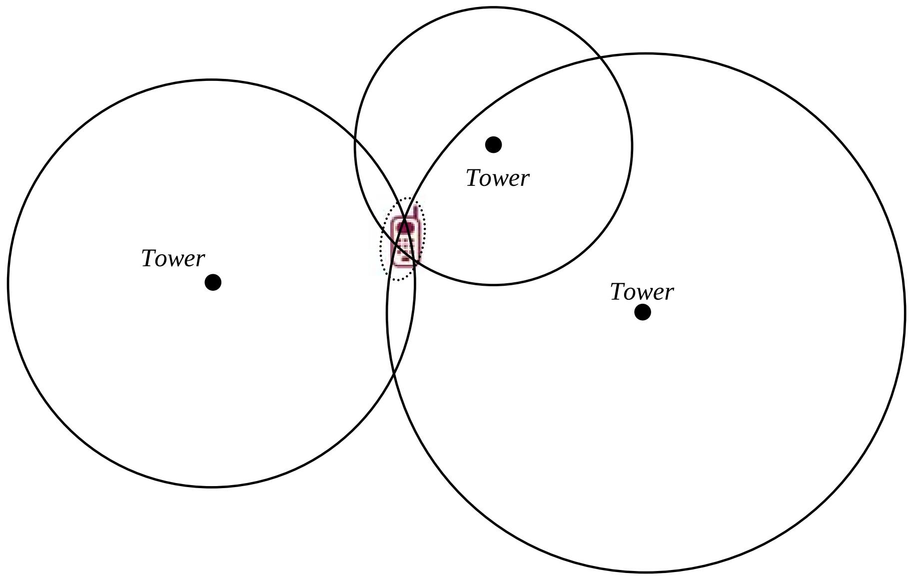


Figure 3-28: Mobile Phone Positioning Based on the Time of Arrival of Signals from Cell Towers.

3.7.3 Signal Strength

Another method of determining position involves the measurement of received signal strength. Such measurements can provide an approximate range between the user's device and the reference stations. A common approach is proximity detection – this approach uses a mobile receiver travelling through an area with a number of fixed transmitters at known locations which measures the power level received from each transmitter. The accuracy of this approach is correlated to the number and geometry of transmitters used and propagation paths between them. If the measured power levels are recorded and catalogued for later use, positioning accuracies should improve.

Examples of positioning systems based on received signal strength are some mobile phone positioning systems, RFID (Radio Frequency Identification) tag readers, or systems that use the known locations of Internet Wi-Fi hotspots to determine approximate location.

These approaches can work very well in indoor and urban environments in developed areas that have been mapped in advance (for first responders in domestic operations, for example), but are less likely to be available to military forces in actual operations.

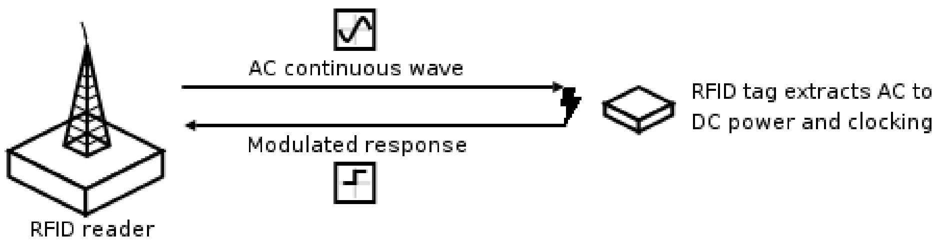


Figure 3-29: An RFID Tag Receives Power and Queries from RFID Readers. The signal strength of the response gives an indication of the range from the reader to the tag.

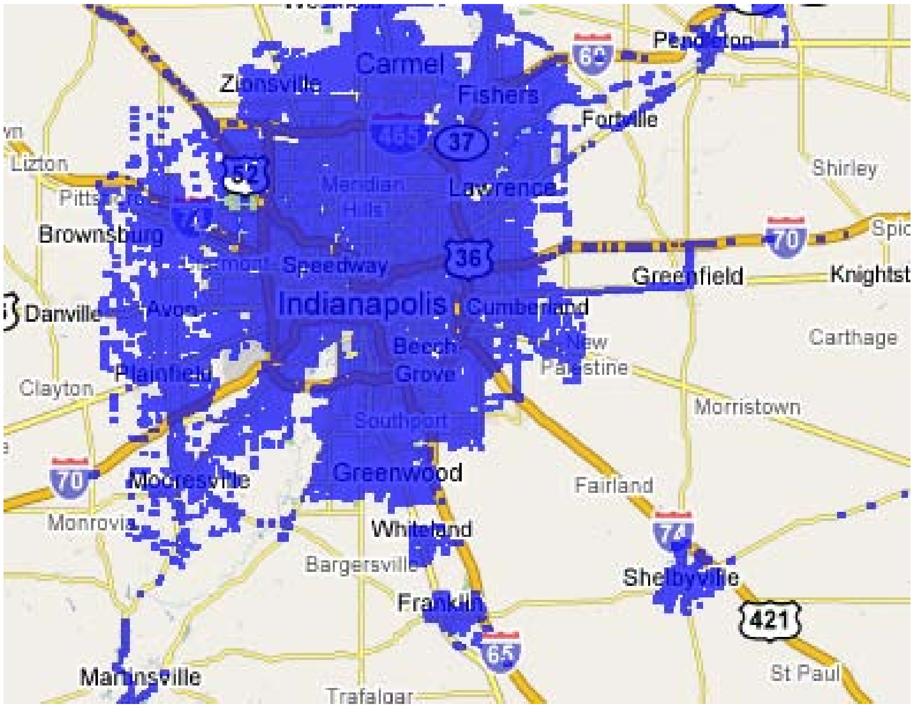


Figure 3-30: Known internet Wi-Fi hotspot locations near Indianapolis are exploited by the Wi-Fi positioning system being developed by Skyhook Wireless Inc.

3.8 SATELLITE NAVIGATION SYSTEMS

Four satellite navigation systems have been designed to give three-dimensional position, velocity and time data almost anywhere in the world with an accuracy of a few meters:

- The Global Positioning System, GPS (USA);
- The Global Navigation Satellite System, GLONASS (Russia);
- GALILEO (European Union); and
- COMPASS (China).

These are all examples of time of arrival (range determination) radio navigation systems.

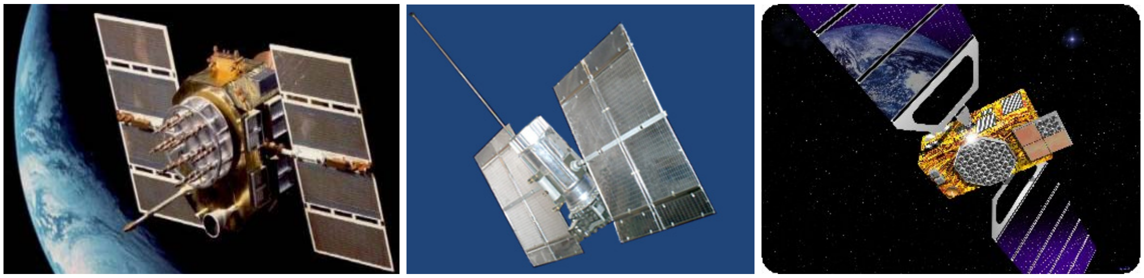


Figure 3-31: Satellites of the GPS, GLONASS and GALILEO Systems.

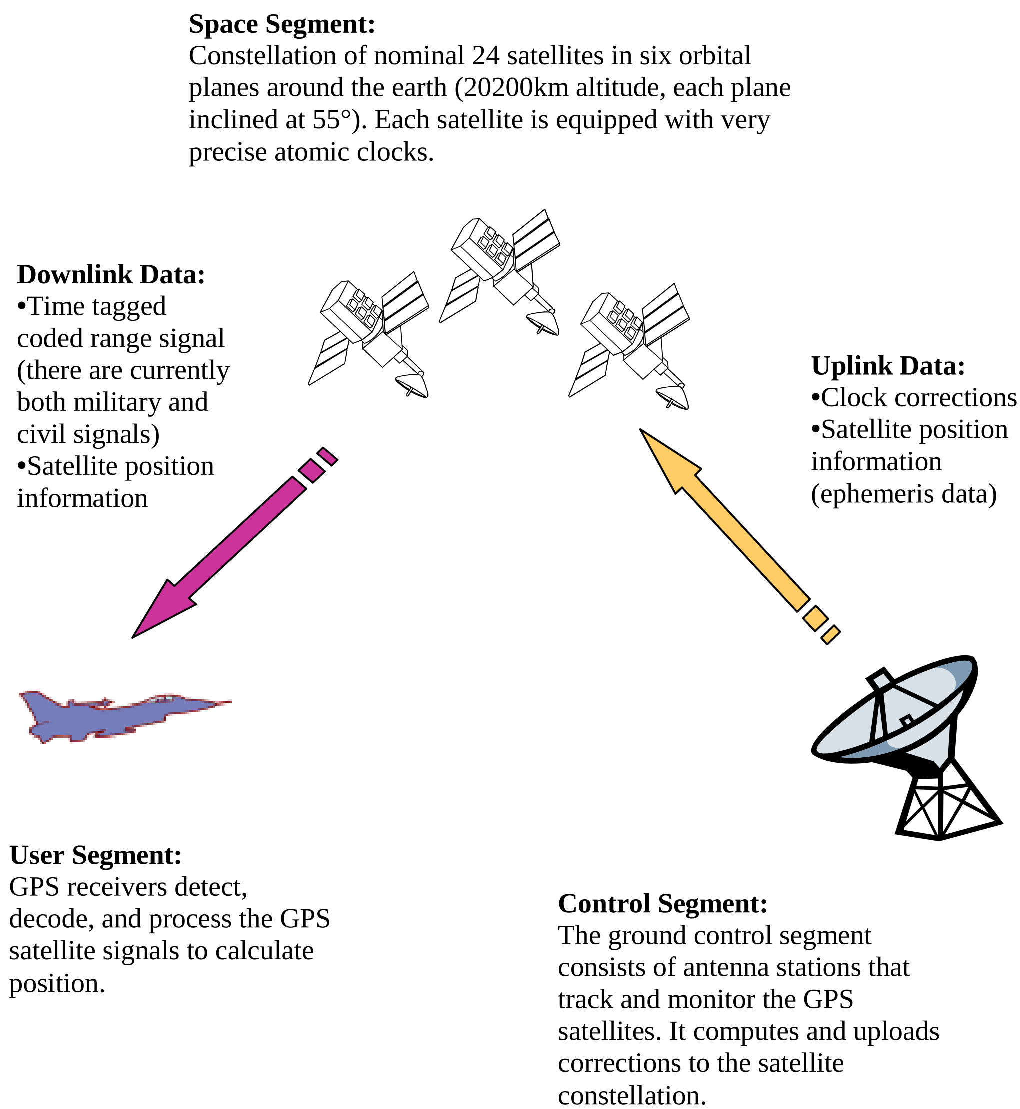


Figure 3-32: Primary Elements of the Global Positioning System.

3.8.1 Satellite Navigation – Principle of Operation

Position is derived by computing the distance from the receiver to each satellite, by measuring the time taken for a signal transmitted from the satellite to travel to the receiver.

In order to make precise distance measurements, the accurate time tagging of the satellite signal is essential – this is achieved with the aid of multiple, but expensive, atomic clocks on each satellite. The clock used in the receiver can therefore be of much lower cost.

Measurements of range to at least four satellites are required to determine four unknowns: three spatial co-ordinates (latitude, longitude, altitude), and time. By using the Doppler shift of the satellite signal, the range rate to each satellite can also be computed in the receiver. This can be used to determine the vehicle's velocity.

Satellite navigation provides a great number of advantages: It provides global coverage, at all times of the day and in all weather; it is very accurate (positions to a few meters, velocity to 0.1 m/s, time to a few microseconds or better); there is no error growth with time; and the user requires only a small, low-cost receiver.

However, there are some significant limitations as well: it is dependent on external signals which may be jammed or blocked by buildings, terrain and foliage; there may be position shifts due to changing satellite visibility; and there may be no signal validation or real-time integrity monitoring.

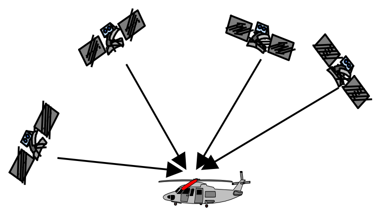


Figure 3-33: Satellite Navigation is a Time of Arrival, Range Determination System.

3.8.2 GPS Augmentations

To increase the accuracy of GPS and provide a measure of its integrity, a number of augmentation techniques and systems have been developed. These are based on differential (DGPS) techniques in which one or more high accuracy GPS reference receivers are installed at known locations and the differences between the measured and known ranges to the satellites are broadcast to other GPS users in the vicinity. This removes much of the ranging errors caused by atmospheric conditions (locally), and satellite orbit and clock errors (globally).

Examples of differential GPS augmentation systems include:

- Maritime DGPS operated by several national authorities for coastal approaches. Corrections are broadcast from shore-based 300 kHz (approximate) beacons.
- Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay System (EGNOS), and other similar systems broadcast corrections and GPS integrity information on the GPS frequencies from geo-stationary satellites.
- Local Area Augmentation System (LAAS) is being installed at some airports to provide high accuracy position and integrity data to support automated GPS-based aircraft landing.

- Assisted GPS receivers, which use information provided by alternate communication channels to aid them in acquiring weakened GPS signals.
- High precision GPS-based surveying systems, employing local differential corrections.

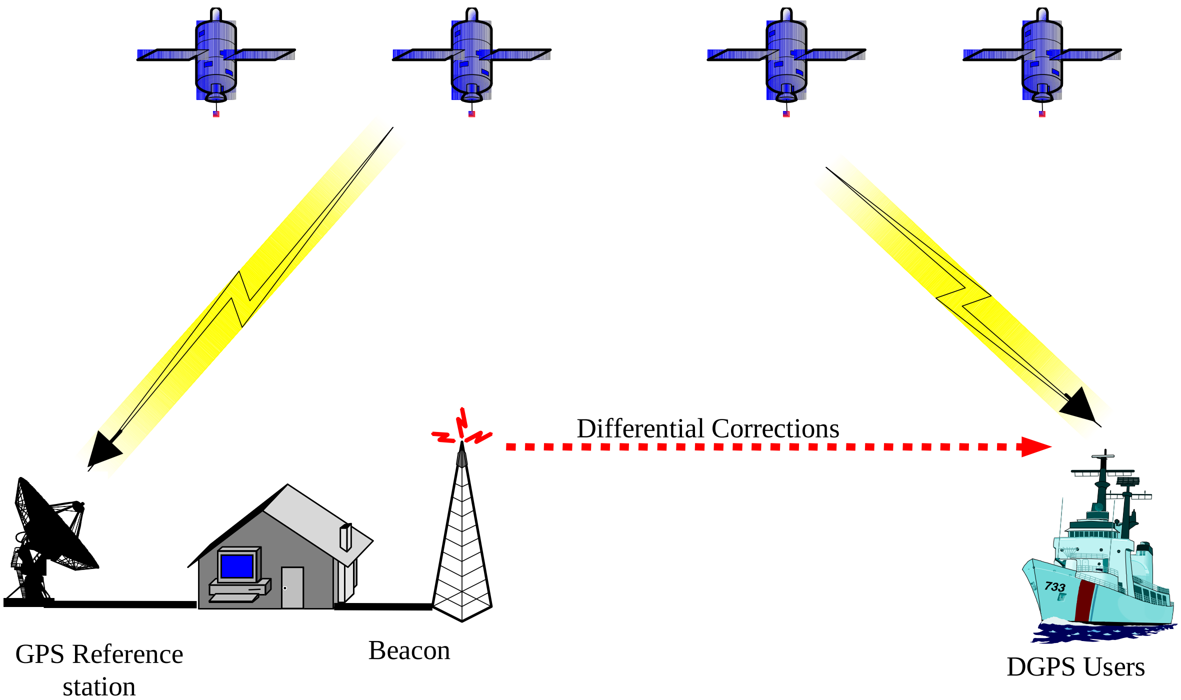


Figure 3-34: Concept of the Marine DGPS System.

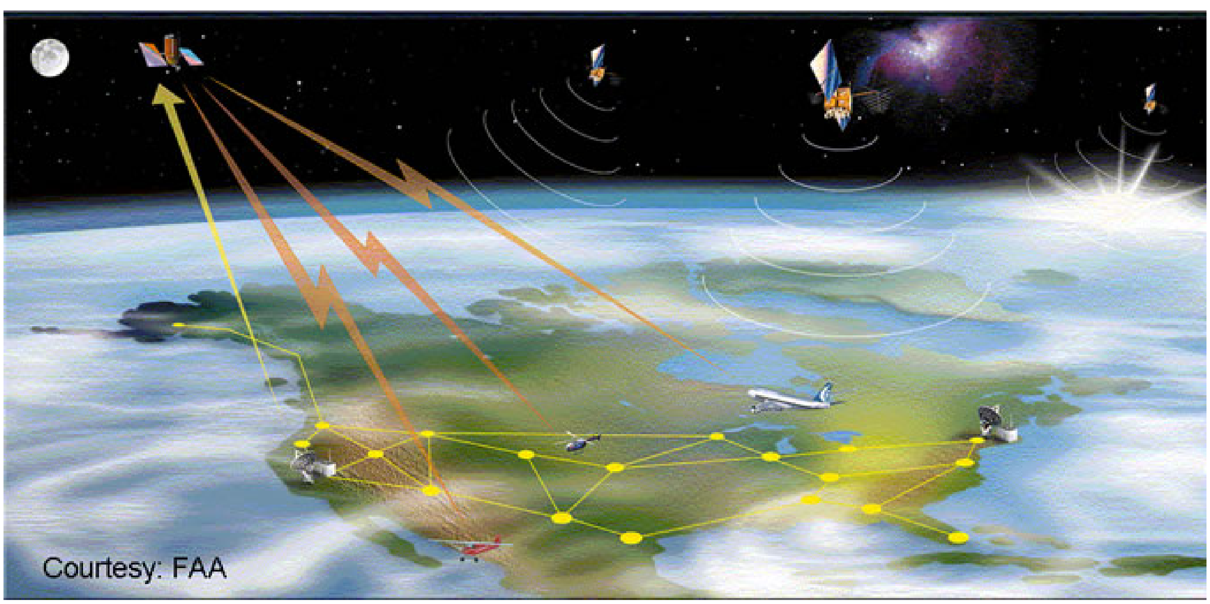


Figure 3-35: The Wide Area Augmentation System (WAAS).

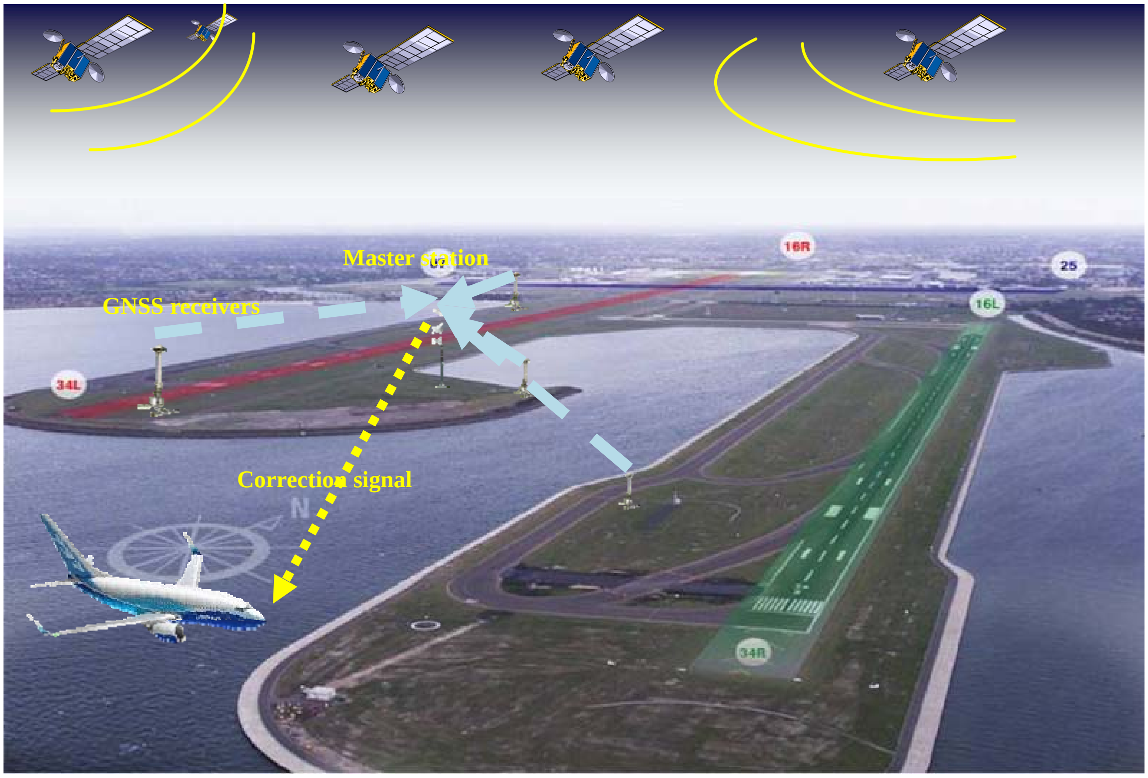


Figure 3-36: The Local Area Augmentation System (LAAS).

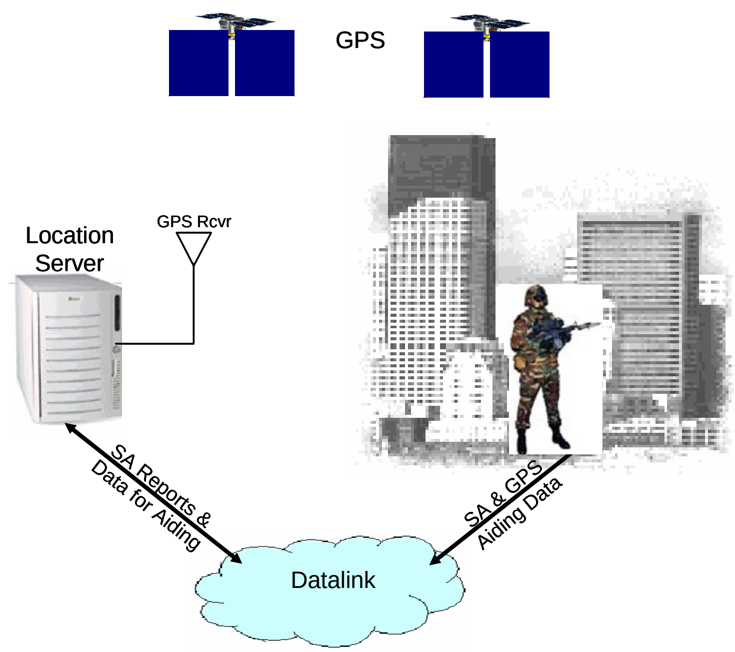


Figure 3-37: Assisted GPS – Time, satellite data, and approximate position transmitted via alternate means to assist a GPS receiver in finding and maintaining lock on GPS signals.

3.9 DATABASE MATCHING

The next major method of navigation is called Database Matching. This technique involves sensing the surrounding environment, comparing this to a pre-stored representation of that environment, and deducing a sensor location and orientation from that comparison.

Examples of database matching techniques include:

- Map matching;
- Image matching;
- Terrain referenced navigation;
- Celestial navigation; and
- Gravimetry.

Some of these are highlighted in upcoming sections.

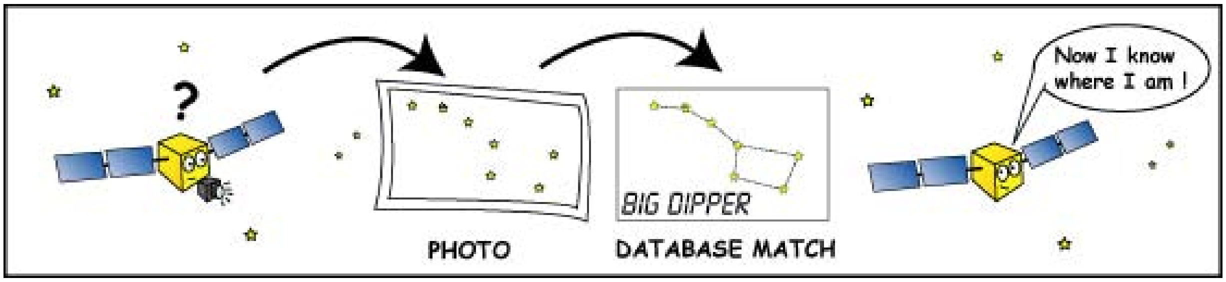


Figure 3-38: Database Matching.

3.9.1 Map Matching

Maps are considered one of the most common aids to navigation. They can be used as a sole means of navigation with users determining their location by feature matching. Alternatively, distinctive map features such as streets, for example, can be used to generate lines-of-position, or otherwise complement or constrain the position generated by other navigation sensors.

The accuracy of map-matched systems is comparable to that of the underlying maps, and the existence of map databases is the key requirement to automating this process.

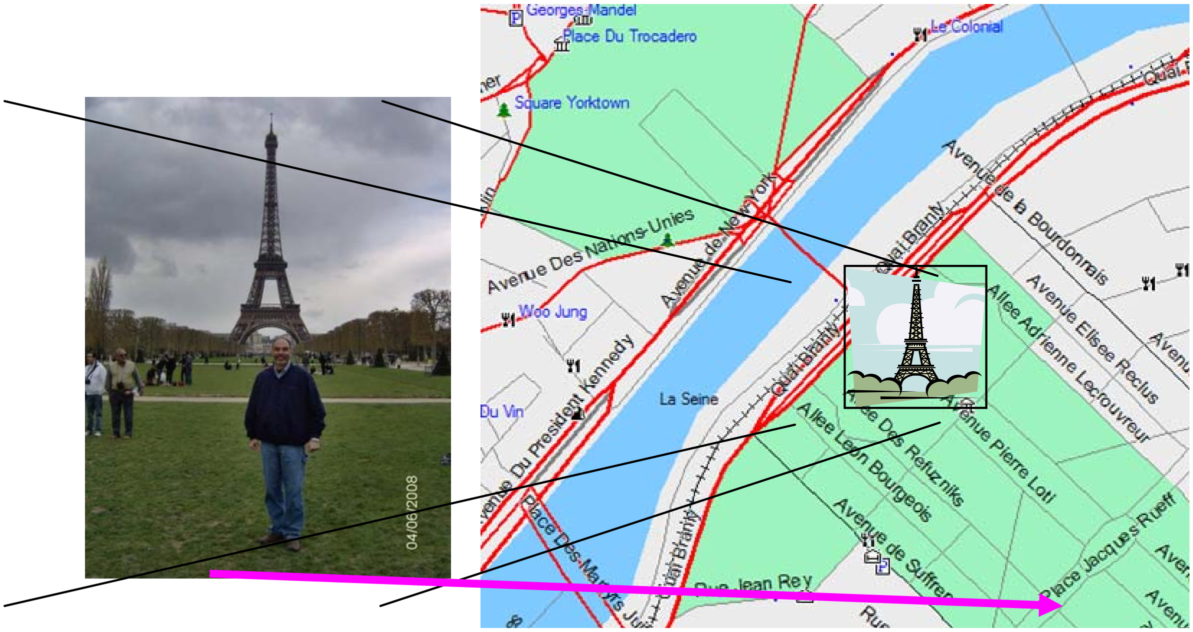


Figure 3-39: Matching your surroundings to a map is a classical navigation method.

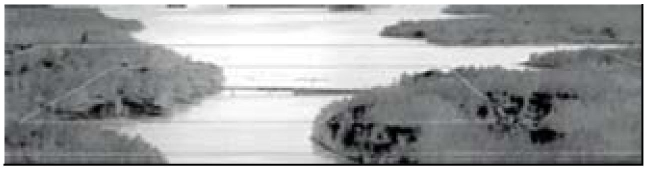
3.9.2 Image Matching

Humans use visual images to avoid obstacles and navigate through their surroundings every day. If points in their images are known to them, they can determine their position.

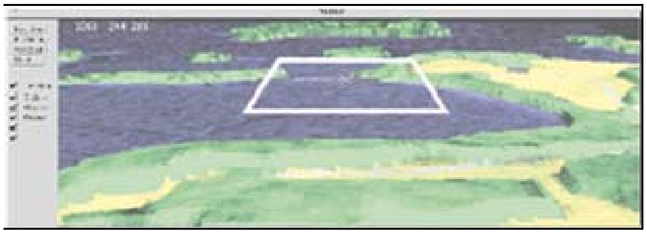
Computerized image-based navigation systems can be organized in two methods:

- **Image Matching**: Given a textured up-to-date surface model of the environment, the position and orientation of the camera can be estimated from a single frame by maximizing the correlation between the observed image and an image database.
- **Spatial Resectioning**: Given only a sparse 3D point or line model database of the area, this method determines the current camera position and attitude from several known points/lines.

Other image-based navigation techniques were discussed in Section 3.2.5. Most recent work in image-based navigation, mainly autonomous robot navigation, has been done in structured indoor environments, which are very easy to model since all the objects are of relatively simple geometry. Error sources are mainly related to the sensor errors and the accuracy with which the image coordinate of the known points can be identified and measured. The limitations to implementing image-based navigation in outdoor environments are due to the difficulties in developing smart algorithms that model such complex environments.



Seeker Image



Database

Figure 3-40: Database Matching in an Optical Image-Based Navigation System.

3.9.3 Laser Imaging

A Laser imaging system traditionally uses a scanning laser diode to measure the ranges to all nearby reflecting surfaces. The resulting laser point cloud is an 'image' of the surrounding area. Position information can be derived if the image can be matched to an existing database. Range measurements from laser imaging systems are very precise: typically better than 0.1 m at 50 m distance and 1 – 5 m at 3000 m.

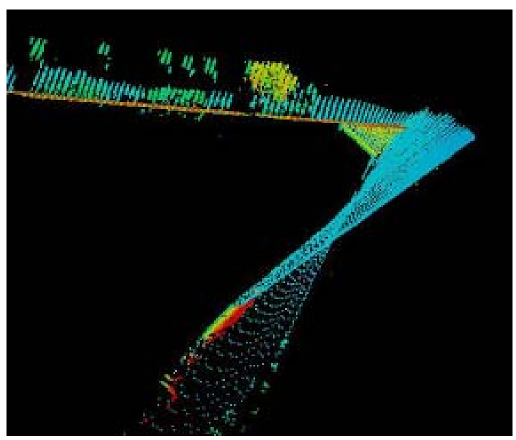


Figure 3-41: Representation of a Wall Ahead of a Scanning Laser (Image courtesy Applanix Corp).

New flash laser imaging systems are an emerging technology that capture multiple point clouds with a staring array at a frame rate similar to that of a video camera. Data processing algorithms can be applied to estimate the motion parameters (see Visual Odometry described in Section 3.2.5) or absolute position coordinates if a database is available for matching.

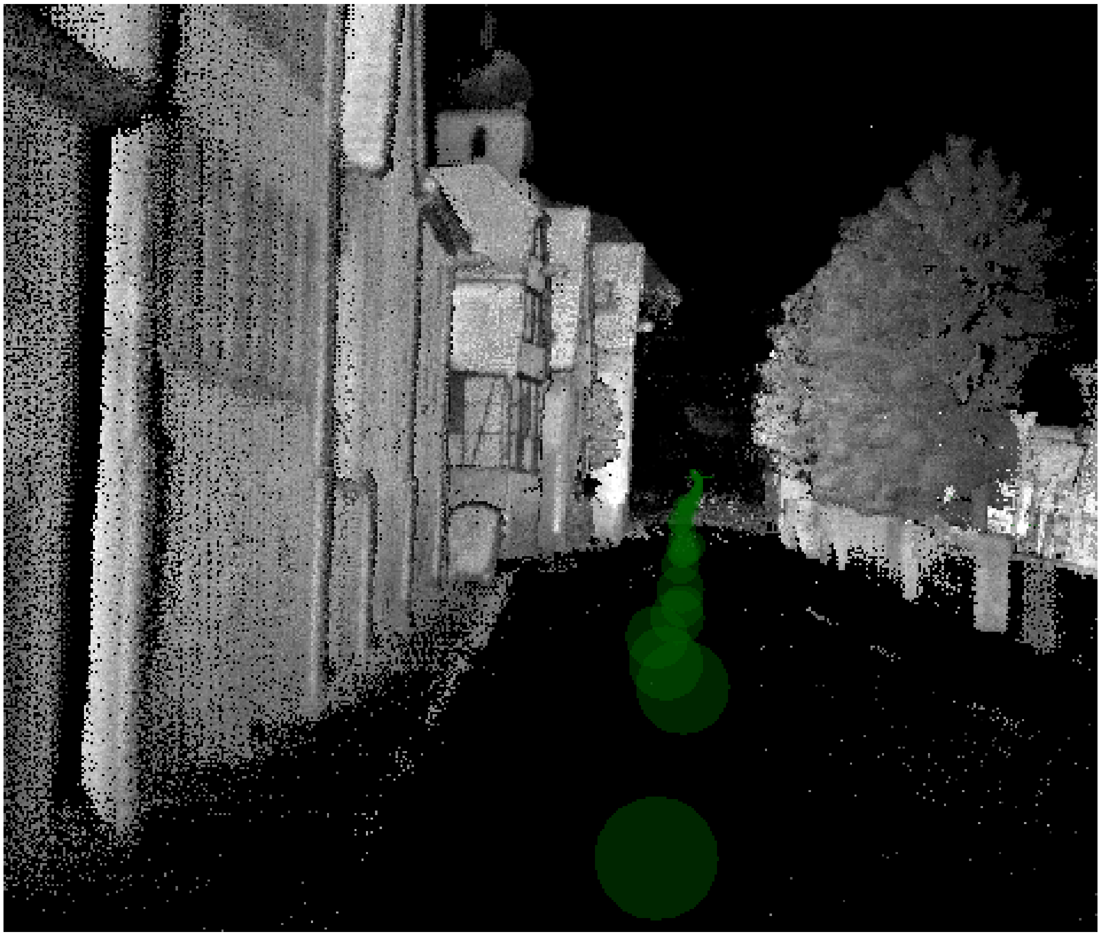


Figure 3-42: Reconstructed Scene and Camera Path for a Forward Motion through a Village. The green dots indicate the estimated projection centers. (Data by the Air Force Research Lab; result by W. von Hansen, FGAN-FOM)

3.9.4 Terrain Referenced Navigation

Terrain Referenced Navigation (TRN) is the name for a group of techniques using sensed terrain height (or depth) information and a terrain database to generate position measurements.

Sequences of terrain measurements are taken and an algorithm then searches the terrain database for a good match with the sensed values. When a good match is found, the approximate route and position of the platform can be inferred.

Typically, INS position and attitude data is used to compute the platform's position from where the terrain sensor measurements are taken. This allows an optimized search of the database. The result of the match is used to improve the current best estimate of position, using a Kalman filter or other data fusion algorithm.

In general, TRN systems are attractive in times of GPS data unavailability because they are virtually impossible to jam, they 'navigate' (relatively) in the co-ordinate system of the terrain/environment, and they operate autonomously (i.e., they do not rely on external systems).

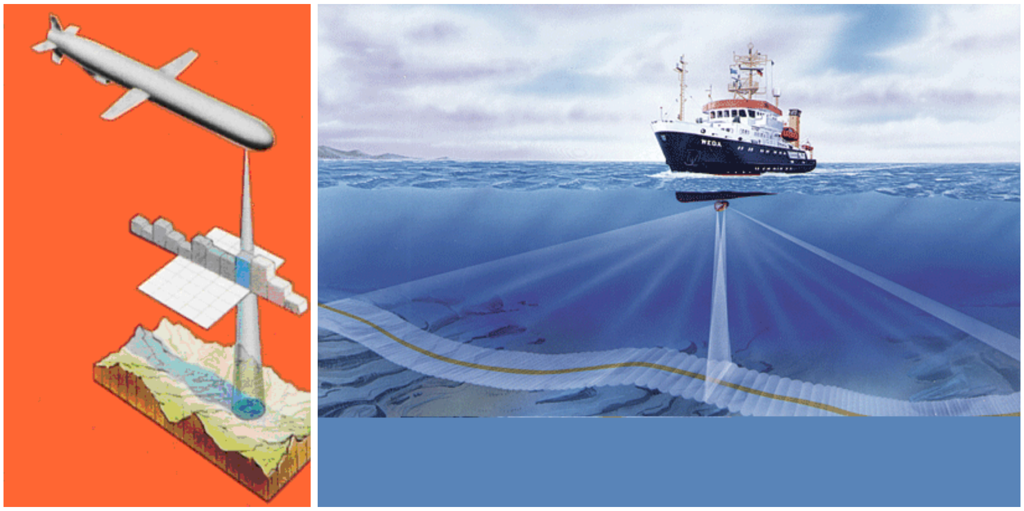


Figure 3-43: Terrain Referenced Navigation by Radar (left) and Sonar (right).

3.9.5 Celestial Navigation

Celestial navigation is the process of finding one's geographic latitude and longitude by means of astronomical observations to celestial bodies, with knowledge of the correct time.

A star tracker combines a telescope and a photo sensor to convert celestial light energy into an electric signal. A sensor is then used to determine where in the field of view the celestial body is, thus providing an output of azimuth. The star tracker is often integrated with an inertial system by a Kalman filter.

Modern celestial navigation systems are able to simultaneously track many stars, thus allowing constellation matching (using an appropriate embedded star catalogue database) which, in turn, improves the accuracy, continuity and robustness of the navigation solution.

Celestial navigation systems are self-contained, provide worldwide operation, and cannot be jammed. They do have potential utility in certain urban navigation applications. However, cloud cover and other obstructions of the sky may preclude their use. Angle measurements on the order of 1 to 2 arc seconds are achievable which corresponds to a positioning accuracy of about 50 to 100 m.

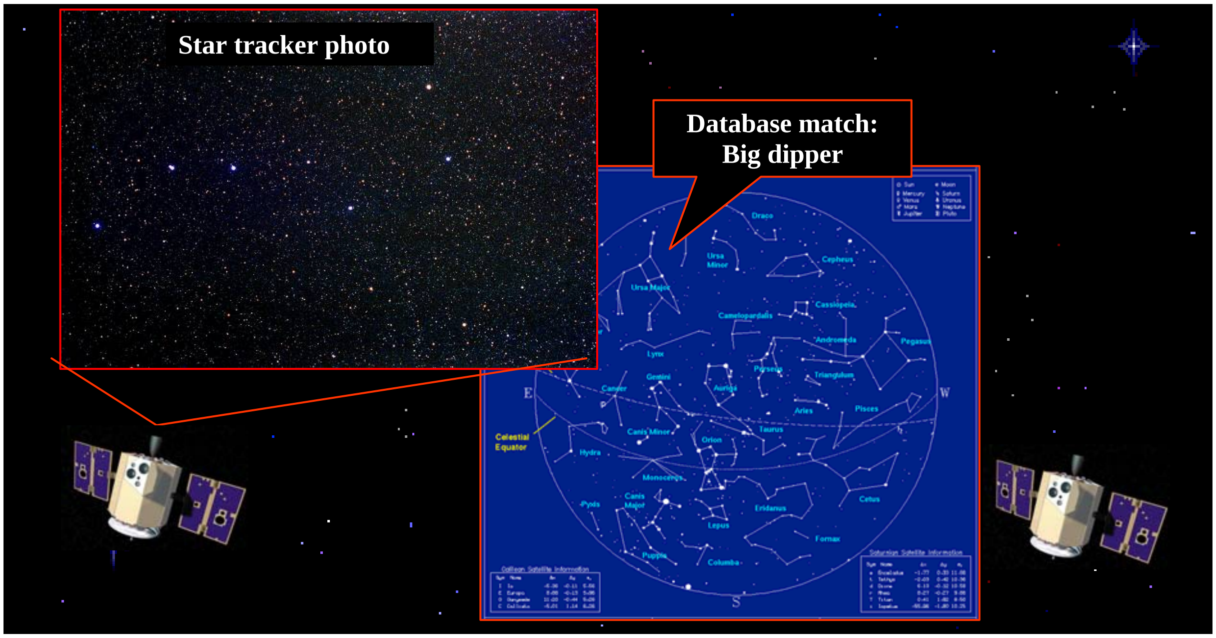


Figure 3-44: Database Matching Used in Celestial Navigation Systems.

3.9.6 Gravimetry

A gravity gradiometer measures the gradient of gravity, i.e., the variation of gravity with distance. By comparing the measured gravity gradient with a database, the location of the gradiometer can be inferred.

Gradiometer navigation has the tactical advantage of being a passive system and is thus stealthy. Unlike established terrain referenced navigation systems, it may also be used over sea and flat featureless terrain. However the granularity of available global gravity maps is coarse and the results are not especially accurate. Local gravity maps may be much better.

Exploitation of measured gravity gradients may be useful in subterranean applications.

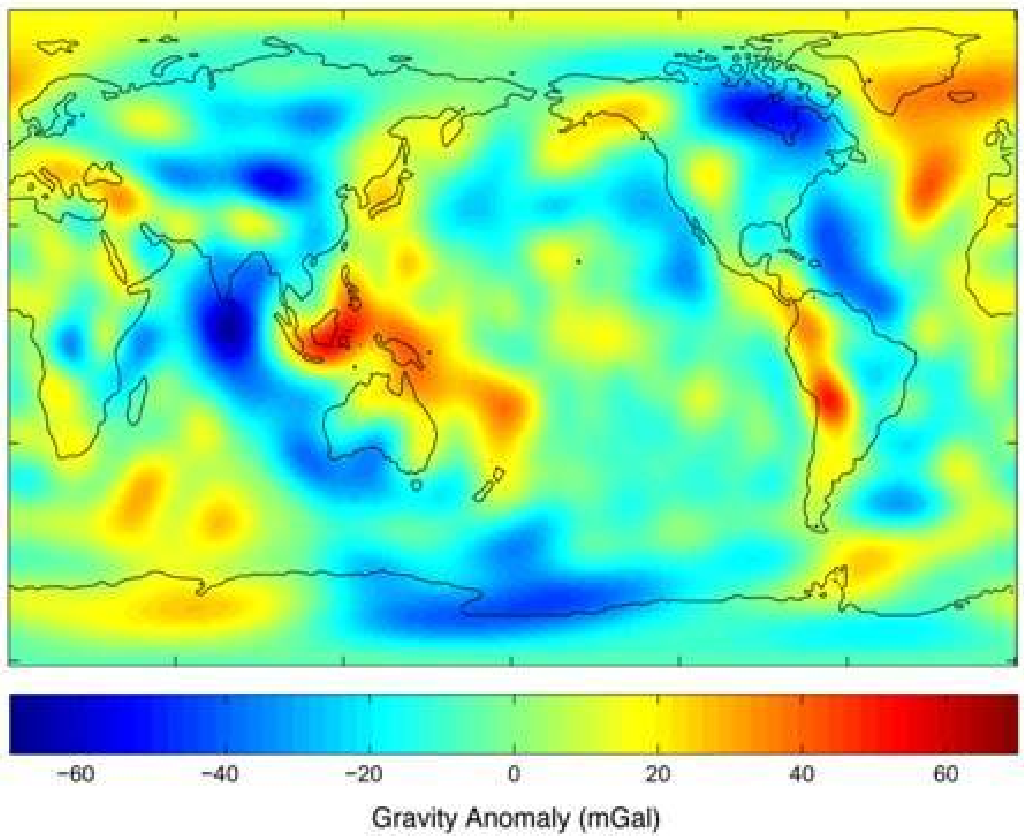


Figure 3-45: A Representation of the Earth's Gravity Field.

3.10 BIO-INSPIRED NAVIGATION

Bio-inspired navigation ([12], [13]) relates to navigation sensors and techniques motivated by nature. Natural systems such as birds and insects rely on navigation sensors and techniques to ensure their survival. For example, birds use vision (landmark navigation), sense of smell (olfactory), and magnetic and sun compasses to navigate during migration, food foraging, and mating. Examples of bio-inspired navigation techniques include:

- Light polarization;
- Landmark;
- Magnetic;
- Echo-location; and
- Olfactory.

Many animals use combinations of several of these techniques and seem to naturally adjust the use of these methods based on their current situations.

Several of these methods are currently being studied with the goal of developing robust integrated navigation systems that will work in difficult environments. Some of these are highlighted in upcoming sections.

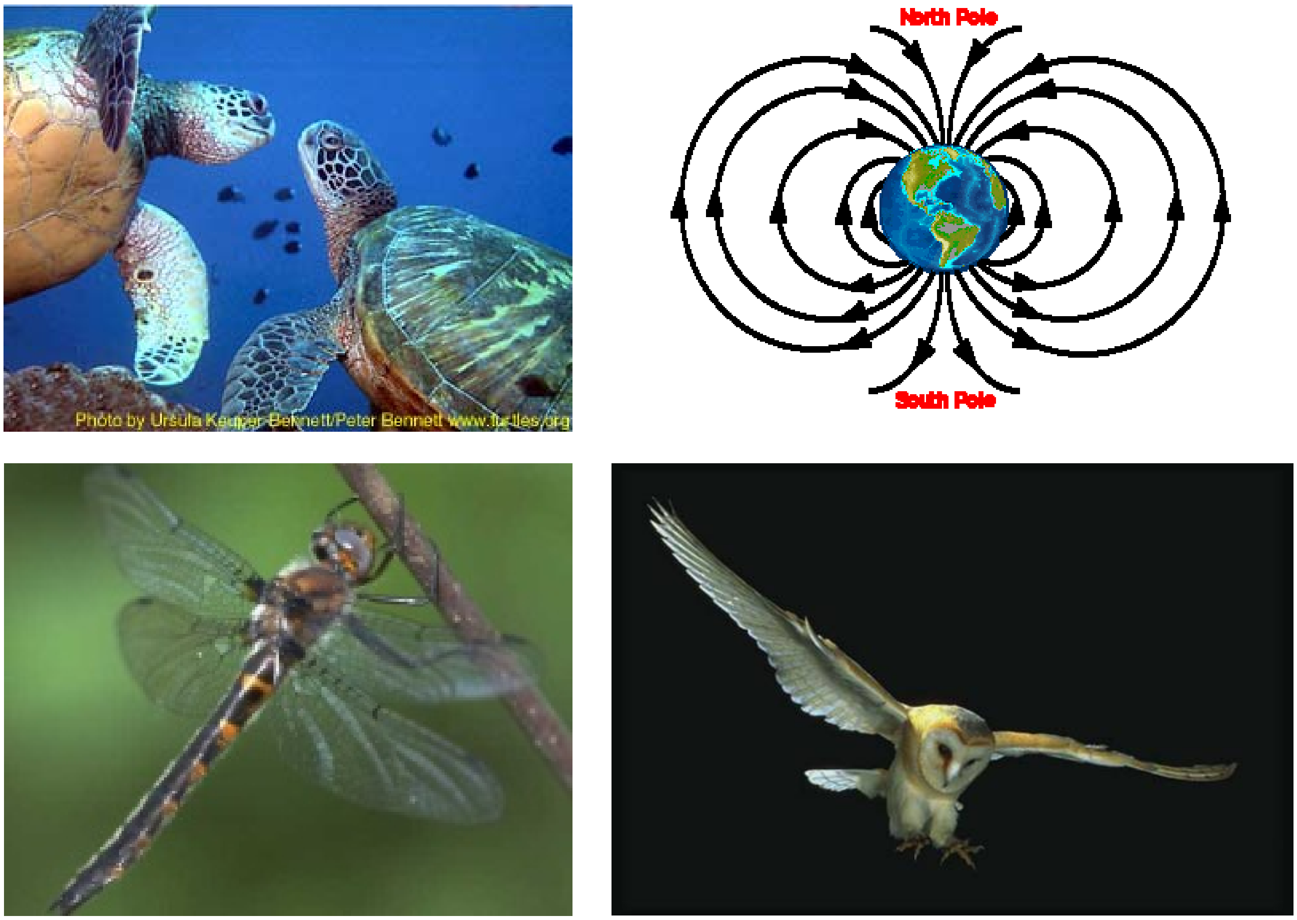


Figure 3-46: Many animals have natural abilities to use various navigation methods.

3.10.1 Light Polarization

Sunlight is scattered by atmospheric molecules and a pattern of polarized light is set up in the sky. This occurs when there are clear or partially clear skies (including partial tree cover and urban canyons), but not when the sky is overcast or at night. For a given sky direction, the sun's polarization will change as the sun moves through the sky, thus providing the basis for a polarization compass and clock.

It is speculated that several biological species, such as bees and ants, have the ability to perceive the polarization of light and use this information for navigational purposes.

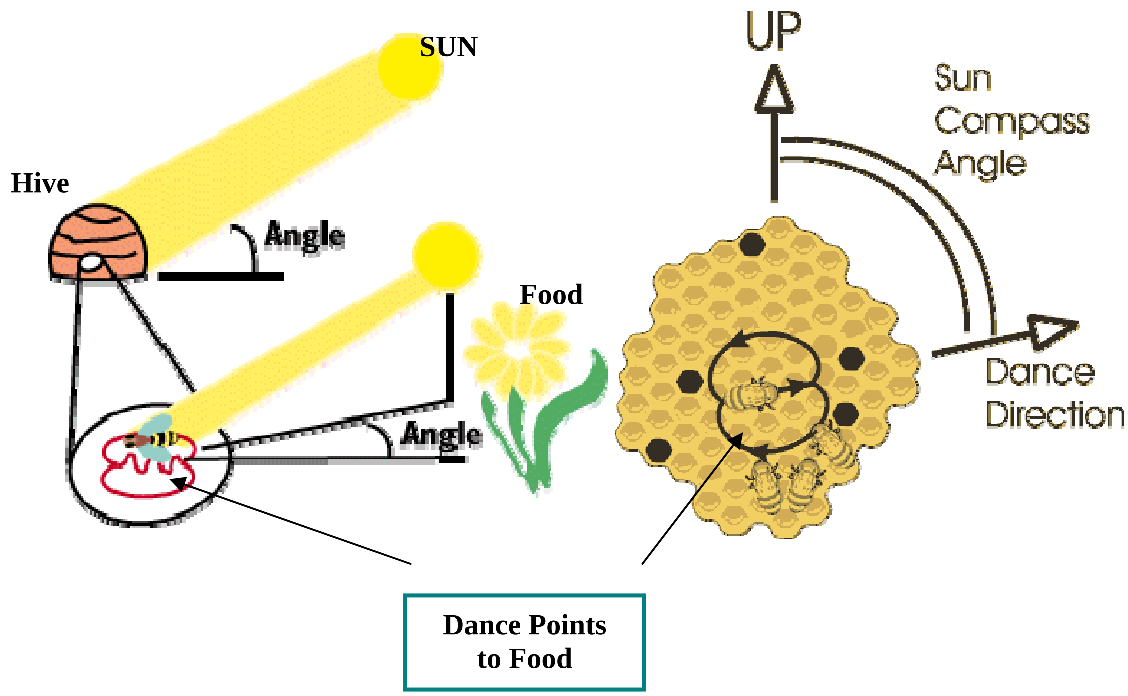


Figure 3-47: Bees can communicate directions with respect to polarized light using various flight patterns.

3.10.2 Landmark

Homing pigeons are known to use landmarks as a navigational aid when returning to a previously established home site. Ants also exhibit a great ability to selectively retrieve and follow landmark-defined routes through various environments. This gives them a powerful method for navigation away from and back to their home site.

Landmark-based navigation is probably the oldest form of navigation used by humans. This navigation technique simply requires the memorization of unique stationary features, which serve as navigational reference points. Early aviators completely relied upon landmark navigation during their air travel. Examples of landmarks include buildings, road intersections and natural landmarks. Other examples of landmark navigation often used by humans were discussed in Section 3.9. They included map matching, image matching, and terrain referenced navigation systems.

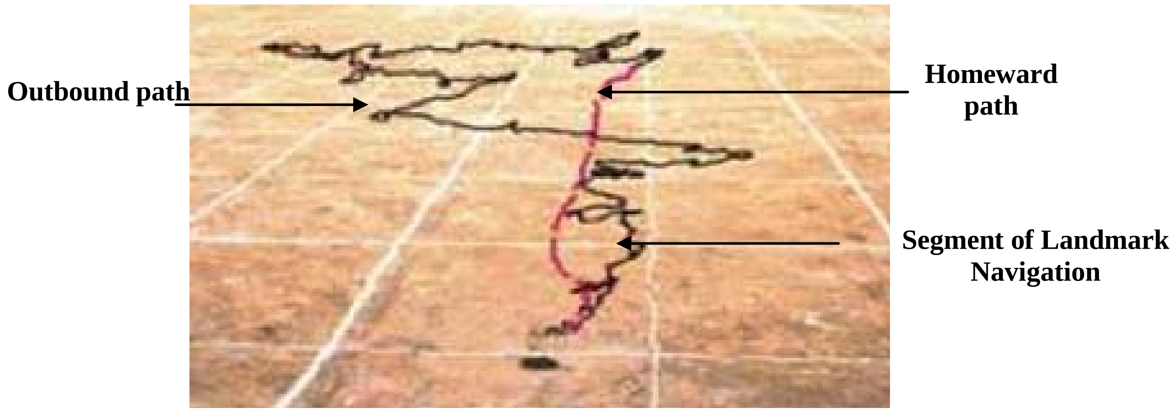


Figure 3-48: The desert ant's navigation skill has been extensively studied by R. Wehner, University of Zürich.

3.10.3 Magnetic

Research indicates that many animal species can naturally sense the Earth's magnetic field and use it to successfully navigate great distances. As an example, sea turtles perceive both the inclination angle and the intensity of the Earth's magnetic field. They use this information both for determining their own geographic location and their desired direction of travel.

The inclination, the angle at which the magnetic field lines intersect the surface of the earth, ranges from 0 degrees at the equator to 90 degrees at the poles. The intensity of the magnetic field also varies in strength over the earth's surface, being strongest at the poles and weakest at the equator.

Older sea turtles use magnetic information in a classical navigational map, allowing them to assess their position relative to their internal magnetic map. This may provide an interesting conceptual design for low-resolution positioning systems.

The concepts described here are the same as used in the Magnetic compass sensor described in Section 3.3.1.

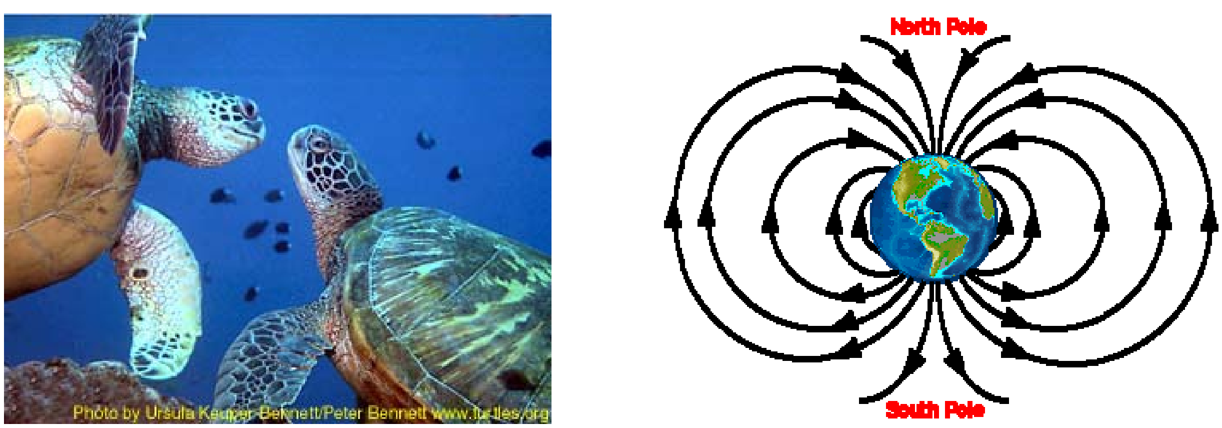


Figure 3-49: The navigation skills of sea turtles have been extensively studied by K. Lohmann, University of North Carolina.

3.10.4 Echo

Echo-location, also called acoustic location or biosonar, is the biological sonar used by several mammals such as dolphins, shrews, and many bats and whales. Echo-locating animals emit calls out to the environment, and listen to the echoes of those calls that return from various objects in the environment. The echoes are used to locate, orientate, range, and identify objects. The animal determines the range by measuring the time delay between the sound emission and the returning echoes. Echo-locating animals generally have two ears positioned slightly apart as shown in the bat picture. The echoes returning to the two ears arrive at different times and at different loudness levels, depending on the position of the object generating the echoes. The time and loudness differences are used by the animals to "see" where it is going; determine an object's size and type; and also determine an object's features.

Currently, sonar is used in submersibles and surface ships to determine the distance to an underwater object (e.g., sea floor) as was discussed in Section 3.9.4.

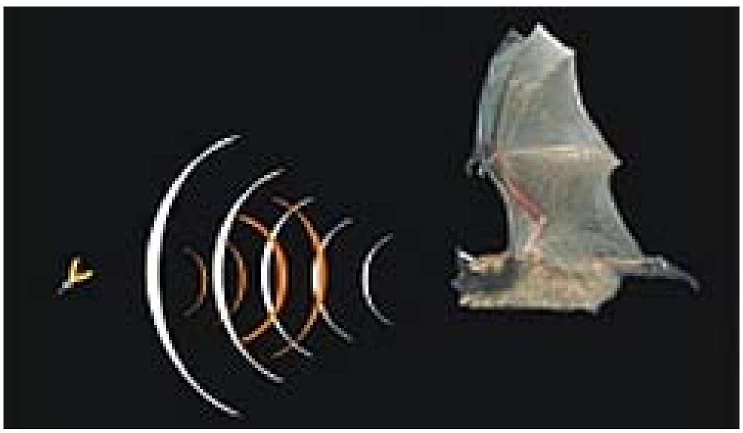


Figure 3-50: Echo-locating is commonly used by many bats (Lake Mead NRA Echolocation Photo).

3.10.5 Olfactory

Olfaction refers to an animal's sense of smell. Specialized sensors are required to detect the odour and determine the direction of the wind (air flow) carrying the odour. Animals steer into the wind and move upstream trying to stay in contact with the odour until they reach its source.

As an example, the figure below depicts a moth's flight track as it tracks an odour upwind to its source. In this image the moth's position is marked with a dot and the orientation of the moth's body is represented by the stick attached to the dot. Of note:

- The moth regularly alters its direction back-and-forth across the wind as it tracks the plume upwind.
- As the moth gets closer to the odour source it narrows its flight track by slowing down and turning more frequently, effectively homing in on the source.

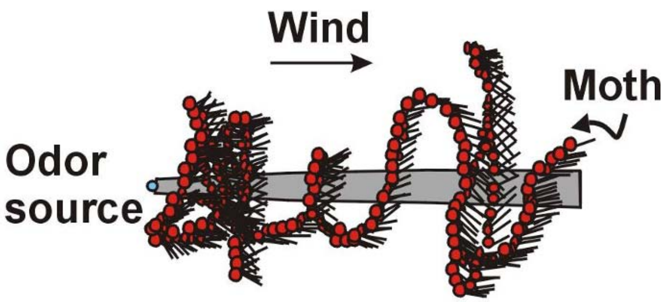


Figure 3-51: The navigation skills of moths as studied by M. Willis, Case Western Reserve University.

Chapter 4 – MULTI-SENSOR INTEGRATION

The concept of an integrated navigation system is to combine the outputs of different types of sensors. Navigation sensors, like anything else, have strengths and weaknesses. For example, GPS has exceptional accuracy, but it is subject to outages due to the loss of satellite signals. Inertial sensors rely only on gravity and platform dynamics, which cannot be jammed, but they exhibit time growing errors that eventually become unacceptable. Through the careful design of the integrated system, the limitations of individual sensor technologies can be greatly mitigated and improved accuracy and robustness can be achieved.

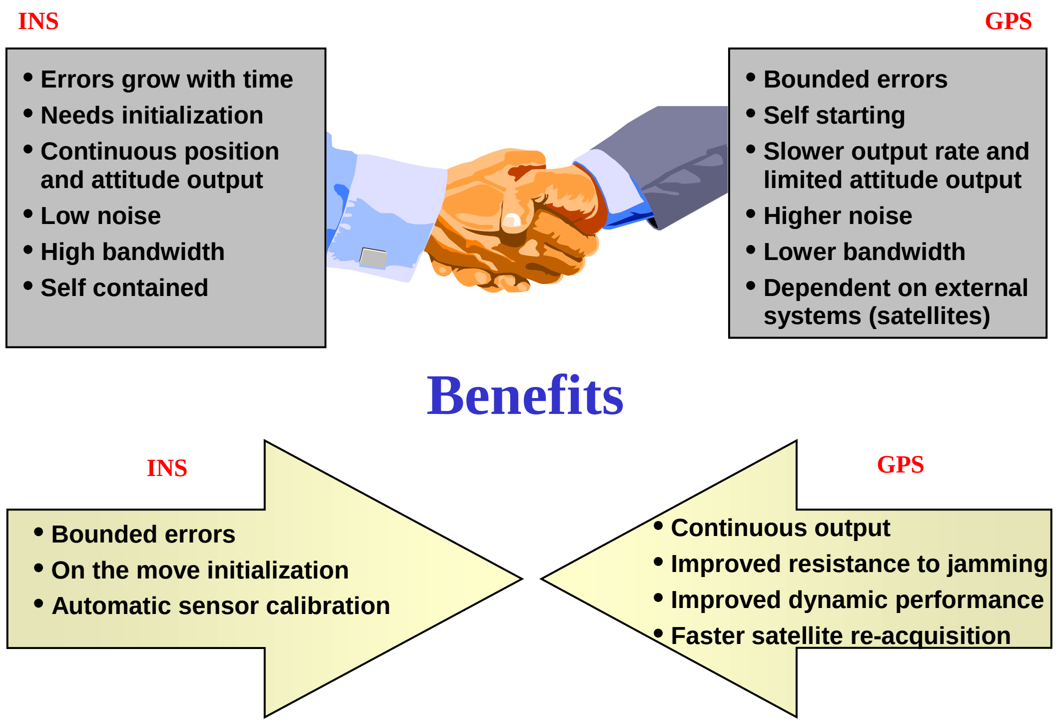


Figure 4-1: The Benefits of Integrating INS and GPS Systems.

The classical method of integrating navigation sensors is called Kalman filtering, following the algorithms developed by R. Kalman in the 1960s. Navigation Kalman filter design requires a careful error analysis and model development for each sensor to be integrated. The Kalman filter will produce the optimal estimate of all the errors in the system given all available sensor data. Three different architectures are in use today: *loosely coupled*, *tightly coupled*, and *deeply integrated* (or *ultra-tightly coupled*) systems. These are described in below, along with some new and innovative alternatives to the Kalman filter, such as particle and sigma-point filtering.

In challenging complex environments, it is quite possible that no one set of sensors will be applicable to all environments. This implies that the ultimate solution will be a modular system in which a suite of sensors can be selected for a given situation and a high level Integration scheme will adaptively integrate those sensors in an optimal fashion.

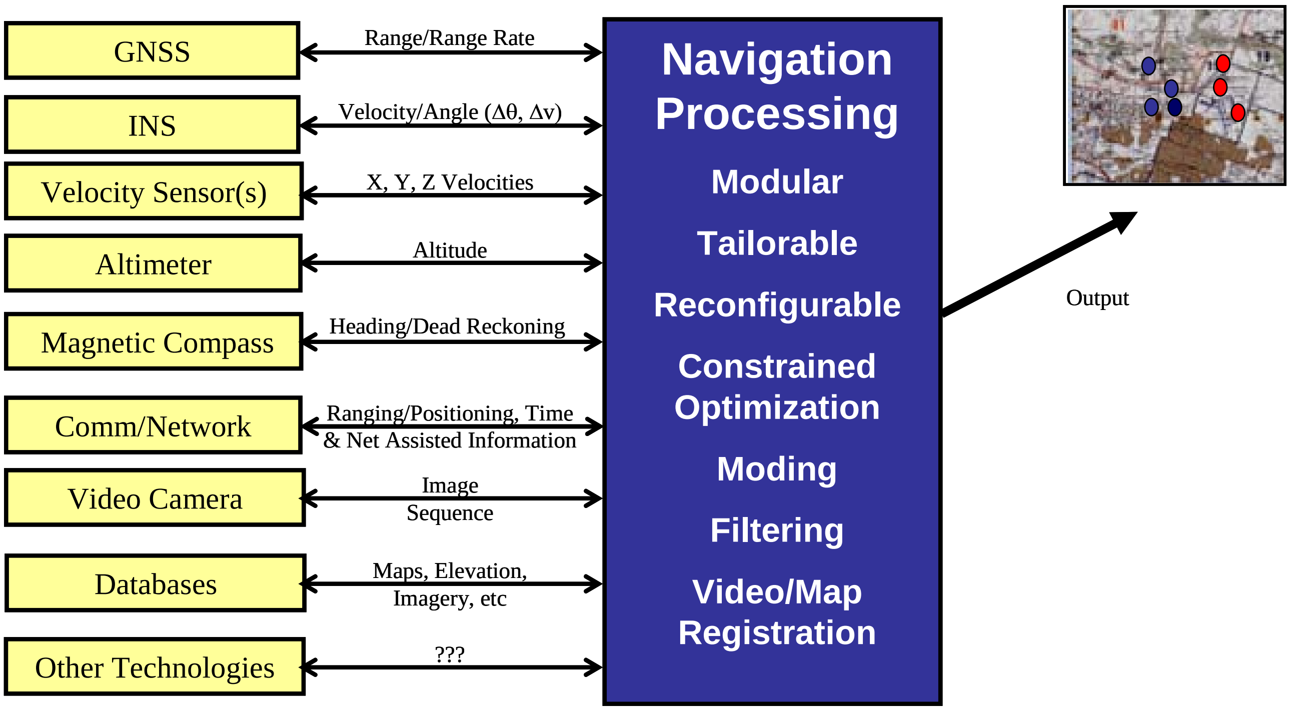


Figure 4-2: Modular, adaptive, multi-sensor integrated systems provide a possible solution to providing robust navigation in complex environments.

4.1 KALMAN FILTER INTEGRATION

Kalman filtering is an algorithm that is used to integrate data from multiple navigation sensors. The Kalman filter will produce the optimal estimate of all the errors in the system given all available sensor data. In most cases the sensor errors are modelled as Gaussian sequences propagating through non-linear models, and a linearization step (based on taking the first derivative of the error model) is required. This linearized version is called an Extended Kalman Filter (EKF).

Three different architectures are in use today: *loosely coupled*, *tightly coupled*, and *deeply integrated* (or ultra-tightly coupled) systems.

4.1.1 Loosely Coupled

In this implementation, a GPS receiver and an inertial navigation system **independently** provide position and velocity data which are blended together in an external Kalman filter. The GPS receiver may or may not have an internal Kalman filter as well.

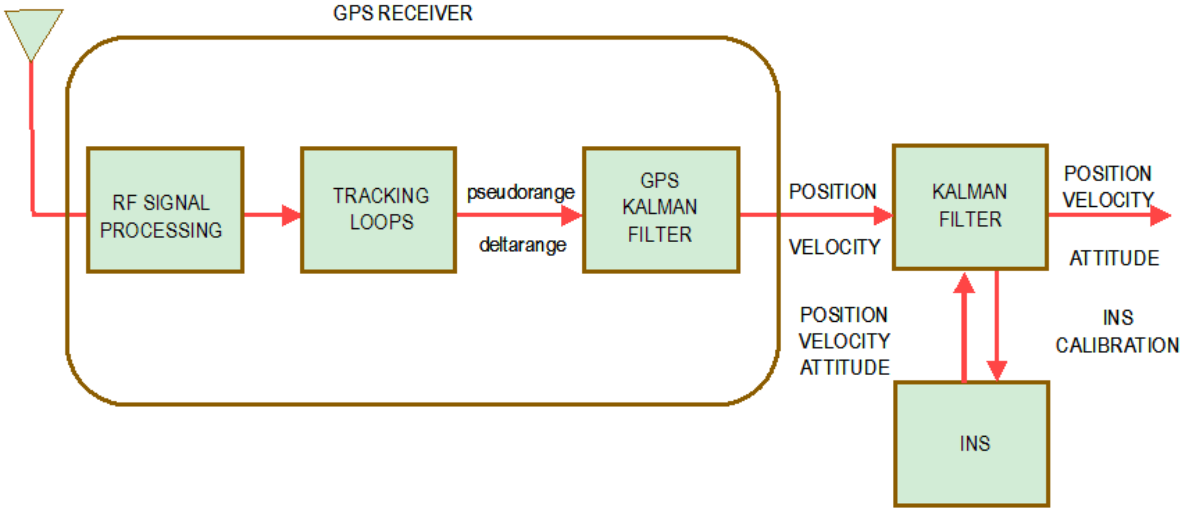


Figure 4-3: The Loosely Coupled Kalman Filter (Schmidt, 2008).

4.1.2 Tightly Coupled

In a tightly coupled system, instead of providing a complete position fix by itself, the GPS receiver provides the raw ranges ("pseudorange" and "delta range") to each individual GPS satellite to the Kalman filter, to be incorporated directly into the navigation estimate with the raw measurements from the inertial system. The INS and GPS modules have been truncated. The GPS receiver now simply provides raw measurements. It does not have its own Kalman filter, but it does still have independent signal tracking loops.

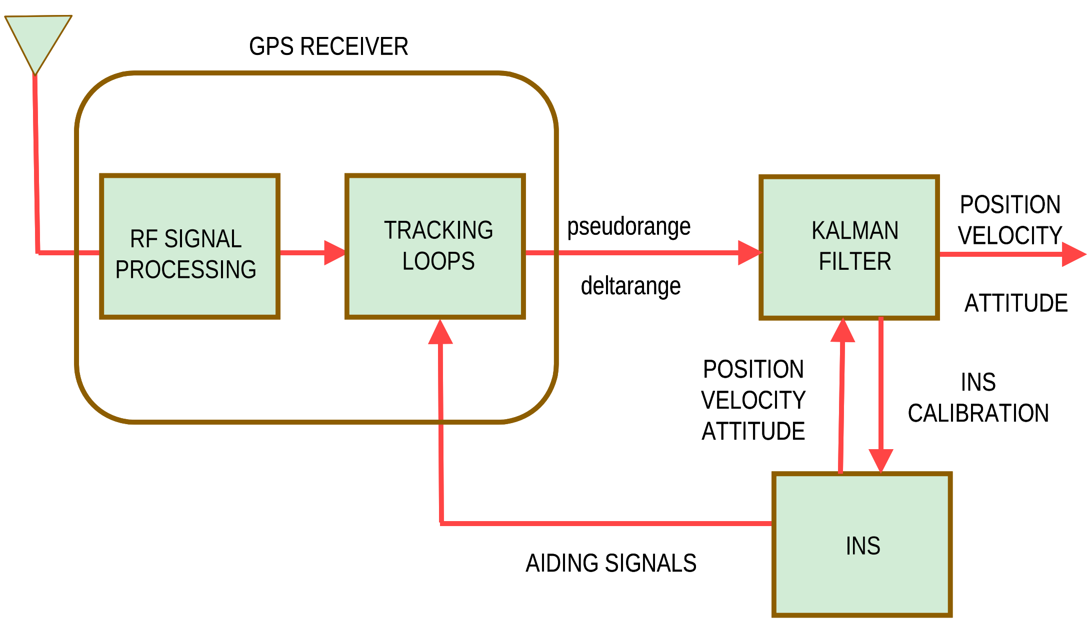


Figure 4-4: The Tightly Coupled Kalman Filter (Schmidt, 2008).

4.1.3 Deeply Integrated / Ultra-Tightly Coupled

In the deeply integrated approach, the notion of separate GPS and INS systems is dropped. The problem is formulated directly as a global optimization in which the best solution is sought for each component of the multi-dimensional navigation state vector. The solutions that are obtained are not based on the usual notions of tracking loops and operational modes. Measurements from all available satellites (SV) are processed independently, and correlation among the Line-Of-Sight (LOS) distances to all satellites in view is fully accounted for. This integration architecture allows simpler, smaller, cheaper hardware to be employed (at the expense of more complex software), and offers better performance, especially in jamming environments.

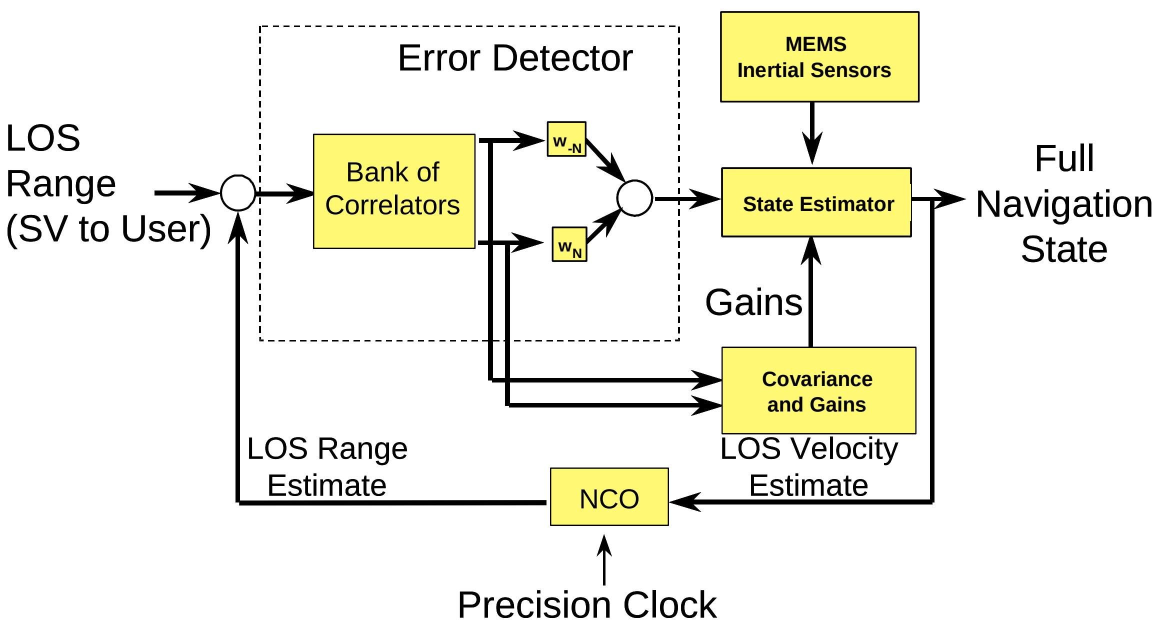


Figure 4-5: The Deeply Integrated Kalman Filter (Schmidt, 2008).

4.2 NOVEL INTEGRATION TECHNIQUES

In recent years, there have been new extensions and alternatives to the classical Kalman filter derived for a number of applications and these are finding their way into integrated navigation systems. Three of those, multiple model filters, unscented Kalman filters, and particle filters are briefly described here.

4.2.1 MMAE – Multi-Model Adaptive Estimation

Multiple Model Adaptive Estimation is an extension of classical Kalman filtering, and in concept is relatively simple. Instead of a single Kalman filter and one set of sensor error models, one can design multiple Kalman filters that operate in parallel. Each filter is based on a slightly different set of error models that better reflect sensor behaviour under specific operating environments. For example, some sensors may have different error characteristics when moving quickly and when stationary, or there may be certain foreseen failure modes that alter the error characteristics significantly and predictably. A separate Kalman filter is designed for each set of models, and their outputs are combined (through a weighted addition, simple voting, or more complex adaptive methods) to derive the final output.

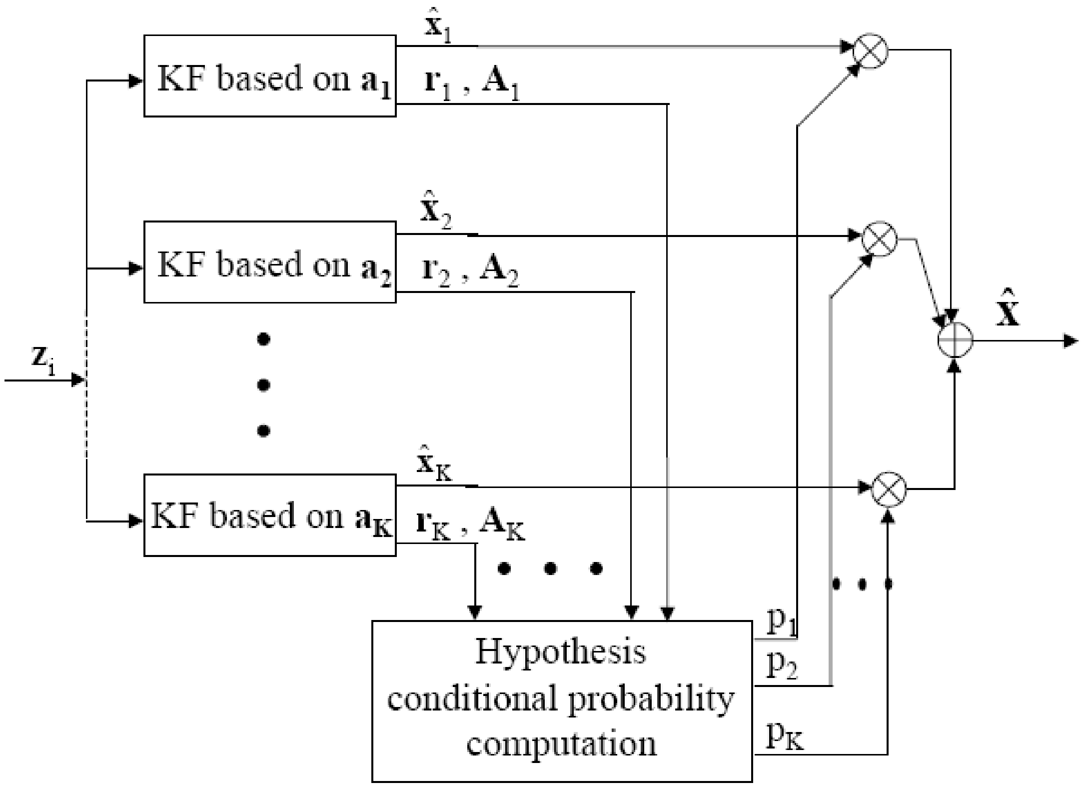


Figure 4-6: Multiple Kalman Filters – each based on a different set of assumptions, operate on the same sensor data in a MMAE algorithm. Their outputs are weighted and combined by a top-level probability computation algorithm. (P. Maybeck, US Air Force Institute of Technology)

4.2.2 Sigma-Point (Unscented) Kalman Filter

The Sigma-Point Kalman Filter (SPKF), or sometimes called the Unscented Kalman Filter (UKF), is a variation of the Extended Kalman Filter for non-linear systems. Instead of the frequent and computationally intensive calculation of the linearization of the error propagation model, an unscented Kalman filter instead maintains the non-linear model and propagates a number of carefully selected data points of the assumed error distribution (called the sigma-points) through the non-linear model to more accurately map the probability distribution than the linearization used in the extended Kalman filter. The SPKF and the EKF have similar performance for systems with small non-linearities, but the SPKF can result in a significant performance improvement when the models are very non-linear.

4.2.3 Particle Filter

Particle filters (also called Sequential Monte Carlo methods) approximate the propagation of non-Gaussian probability distributions through non-linear systems with many random samples, named particles. The particles in an integrated navigation system are representative samples of the state vector. The notion is to track the weighted sum of a number of particles as they evolve through the non-linear system. As the number of particles goes to infinity, the estimates converge on the true probability distributions of the true state vector under very weak assumptions. However, for practical implementations, a finite number of particles must be used and so there is ongoing research into determining the best choice of particle samples.

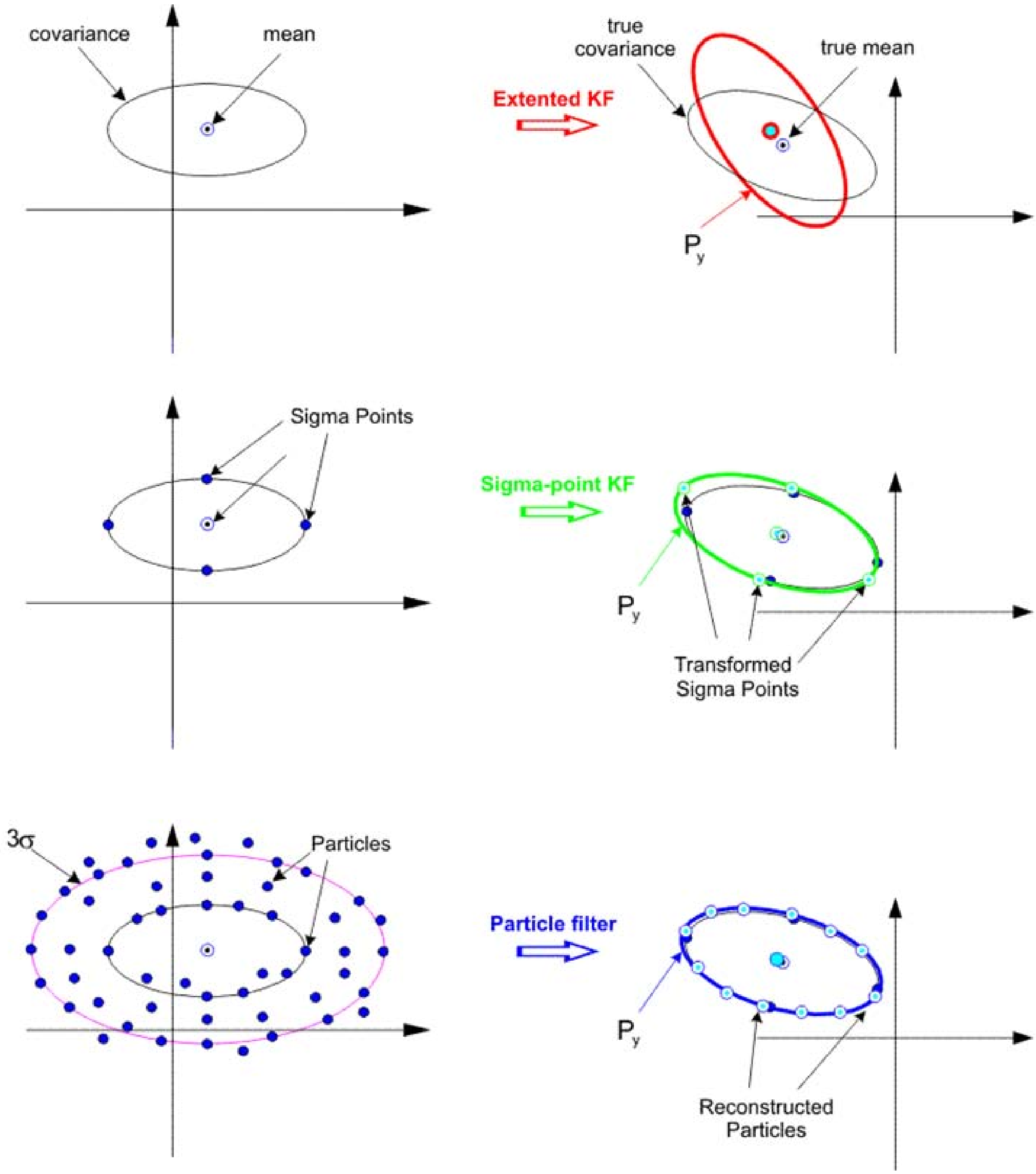


Figure 4-7: Sigma-point Kalman filters and particle filters are being studied for Implementation in non-linear systems. Samples of the navigation state are propagated through a non-linear system model. A traditional Extended Kalman Filter approximates the non-linear system with a linear simplification. (M. Sotak, 2007)

Chapter 5 – EMERGING MILITARY CAPABILITIES

This section of the report identifies emerging military capabilities enabled by new navigation sensor technologies and techniques which allow operation in complex environments. Examples of complex environments include urban, indoor, and subterranean, where GPS is often not available due to signal occlusion or jamming (intentional or unintentional). Many other applications could also be envisioned by the use of the navigation technologies outlined in this report. This section also discusses future requirements and potential research areas. Introductory information for several of the capabilities listed Table 5-1 is given below.

Table 5-1: Emerging Military Capabilities.

Higher Situational Awareness	Friendly force tracking
	Enhanced net-centric warfare
	Distributed sensors / synthetic aperture
	Reduced fratricide
	Identify Friend or Foe (IFF)
	Enhance cooperative engagement
	Mine Counter Measures (CM)
	Logistic tracking
	Training instrumentation (scoring)
	Search and rescue
Operations in Urban, Indoor and Subterranean Environments	Navigation in urban terrain, indoors, and caves
	Aggressive maneuvering (e.g., flight below tree canopies)
	Dismounted soldier navigation (plus Special Operations Forces (SOF))
Unmanned Navigation (Unmanned Applications / Force Multiplication)	Parafoil delivery
	Micro/mini unmanned autonomous systems, i.e., smart “bugs”
	Unmanned logistic vehicles
	Underwater vehicles
Weapons Effectiveness (Aiming / Guidance / Target Location)	Smart munitions
	Precision targeting (location)
	Reduced collateral damage
	Greater artillery effectiveness (trajectory shaping, mass)
	One hit per round
	Reduced seeker complexity
	Turret stabilization

5.1 HIGHER SITUATIONAL AWARENESS / NETWORK-CENTRIC WARFARE

The traditional role of position information was for "own ship" navigation. That is, "can I find my way from Point A to Point B?" The evolving role of Position, Navigation, and Time (PNT) information as a shared resource to establish friendly force situational awareness is to enhance command and control effectiveness for force multiplication. Improved situational awareness, whether it is for the dismounted warrior or the logistics chain, is critically dependent on the knowledge of time, position, direction and speed of movement. Not only can PNT knowledge assist in the Identification of Friend or Foe (IFF) to reduce fratricide, it is critical for cooperative engagements.

Thanks to the information age and the near-instantaneous transfer of information, a fundamental shift from platform-centric warfare to Network-Centric Warfare (NCW) is occurring. The future battle space will feature networks of distributed sensors and weapons platforms. NCW enables operational concepts that generate increased combat power by networking sensors directly to decision makers and shooters. This networking allows greater synchronization, shared awareness, increased operational tempo, higher speed of command, greater lethality, and increased survivability. The foundation of this concept is that all platforms have instantaneous knowledge of their own positions, and those of all other cooperative network entities. Given this knowledge, the goal is to know where enemy personnel and equipment are operating and pass this information to all cooperative network agents to enable effective enemy engagements.

For NCW to be extremely reliable and successful in future combat operations, highly accurate, precise, and robust PNT information with high integrity must be available in all combat operating environments and locations. If satellite-based navigation systems are the only sources of PNT data then, as discussed throughout this report, in difficult urban, indoor, subterranean or GPS-denied environments, accurate PNT data will not be available. This directly impacts NCW operations since each sensor's data will be severely degraded due to the inability to synchronize and geo-reference each sensor in the battle space. Thus, there is a strong requirement for improved PNT sensors and techniques to ensure NCW concepts will be successful in any environment at any location.

5.2 OPERATIONS IN URBAN, INDOOR AND SUBTERRANEAN ENVIRONMENTS

A very important emerging military capability enabled by advances in navigation sensors will be the ability to obtain precise positioning and navigation information by forces operating in difficult RF environments such as indoors, in urban canyons, under heavy foliage, and in underground or underwater environments. With today's asymmetric threat, the combat arena is increasingly becoming focused towards operations in these types of environments.

Such precision location information allows many new capabilities that are very difficult, time consuming or virtually impossible to do today. For example, with a sensor system that can accurately track a user to within one meter deep inside a building or cave structure, the improved situational awareness will allow each user to pinpoint their own location on a schematic (if one is available) and be able to show them their way should they become disoriented. It would allow commanders to know exactly where all friendly platforms are at all times, allowing improved friendly force protection and evacuation of personnel when required. For areas in which detailed maps are not available, such a system would allow precision maps to be made on the fly as the platform traverses through the environment. Cooperative engagements by separated platforms become much easier and battle commanders can aid in the direction of forces towards objectives and rendezvous points should the personnel be unable to monitor their own navigation system.

Traditional satellite navigation systems have difficulty in providing sufficient power at the surface of the earth to allow today's GNSS receivers to obtain the minimum signal power levels required to operate in urban or underground environments. With the ability of the satellites to generate more power quite limited, advances in other technologies will be the key to enabling the capability. The appropriate technical solution will be a multi-sensor solution. The key component will likely be a high quality micro inertial system integrated with various low-cost sensors such as; electro-optical, laser, or ultra-wideband systems, and supplementation with dead reckoning sensors such as magnetic compasses, step sensors, air speed sensors, or combinations of these. There is a reasonable expectation that the capability will exist within the next 5 – 10 years.

5.3 UNMANNED-PLATFORM NAVIGATION

The decreased cost, volume, and power requirements of navigation sensors together with their improved reliability and accuracy has allowed the possibility of eliminating human operators from many military platforms. Systems once thought suitable only for high-value manned platforms are becoming more commonly used in unmanned vehicles (air, sea, underwater or land). The challenge is to integrate the navigation sensors, control algorithms, and artificial intelligence to avoid obstacles and follow the optimum track in order to complete the desired mission. Future autonomous systems will require multi-use sensors capable of providing both navigation and Intelligence, Surveillance, and Reconnaissance (ISR) updates to the networked environment.

5.4 WEAPONS EFFECTIVENESS

The improved ability of ballistic weapons or munitions to have detailed knowledge of their own positions and orientations in the battle space relative to the aim point allows a weapon system to substantially increase its lethality resulting in fewer rounds/munitions per target, decreased collateral damage and more effective use of valuable resources. A related use of small navigation sensors is the stabilization of weapons platforms, e.g., tank turrets, enabling accurate target engagement while on the move. These applications are becoming more commonplace due to reduced size and cost brought on by advances in navigation sensor technology.

As the navigation sensors become even smaller, cheaper and robust enough to withstand even gun-launched environments, a new family of guided weapons has been created. Such munitions can determine their own positions and navigate themselves towards their targets (aim points), requiring the use of one or more navigation sensors. The navigation systems have to withstand very high launch dynamics, harsh handling and operating conditions, and they must be very affordable. Such systems are becoming a possibility due to cost and size reductions and increased shock survivability provided by new navigation devices such as MEMS inertial sensors. These MEMS sensors can survive 15,000 to 35,000 g gun launch shock.

The complexities of the battle space and moving targets may require the addition of different seeker or communication systems to the munition to increase hit probabilities. Even in such cases an ability to navigate until control is transferred to the seeker has the advantage of limiting the search space, potentially decreasing the complexity and cost of the seeker.

5.5 SUMMARY

While it is possible to achieve the required performance levels for many of the above applications, typically such systems are too large, expensive and/or fragile for widespread use. Advances in navigation sensors have bridged this gap in many applications. Continued innovations in technologies such as MEMS-based inertial

components will further increase the use of navigation technologies in many other applications, decreasing costs as the technology and production techniques mature. Research and development in alternate and novel navigation techniques, such as those inspired by nature, is required as systems need to become smaller and operate in more demanding and complex environments.

Chapter 6 – CONCLUSIONS

This report documents the work of Research Task Group (RTG-065) on “Urban, Indoor and Subterranean Navigation Sensors and Systems”. It summarizes the work of the RTG, including descriptions of the products generated by the Task Group, and provides a technical overview of new and emerging navigation sensor and system technologies that will impact future military operations worldwide.

During its existence from 2006 to 2009, the group organized a Symposium, a Lecture Series, produced a handbook on advanced navigation technologies, and generated this final report.

Recent advances in inertial and satellite navigation, as well as traditional RF (Radio Frequency) and non-RF navigation aids, are being matched by a tremendous amount of on-going research and development in new and innovative sensors and integration techniques rarely seen before. The motivating factor for much of this research is the fact that satellite navigation is not the best approach when operating in challenging environments where the signals may not be available or may be denied. This report has highlighted other areas of research and technology that, when combined with an inertial navigation system, may be more applicable to these challenging environments. Areas of technology ranging from dead reckoning techniques (such as velocity and distance travelled sensors, heading sensors and altitude/depth sensors) to externally dependent systems such as pseudolites and signals of opportunity have been covered. Database matching systems, such as terrain referencing, are also discussed. Imaging sensors such as visual, thermal and laser-based are advancing rapidly and navigation systems exploiting these devices are also covered in this report.

One area that bears watching in the near future is the research being done to study the mysterious techniques that birds, animals and insects use to navigate. From bees returning to their hive to birds migrating half-way around the globe, nature has an inbuilt capability to navigate with remarkable accuracy and repeatability. Are there natural techniques that can be exploited to develop militarily useful technologies? It remains to be seen and is an interesting question.

The report has also explored the enhanced military capabilities that will result from these advances, such as higher situational awareness, greater weapons effectiveness, more reliable operations in urban, indoor and subterranean environments, and enhanced unmanned-platform navigation.

Almost all of the networked, collaborative systems being developed or envisioned today require an exact knowledge of position, orientation and time data to be able to fulfil their objectives. Generally this navigation requirement is pivotal to the success of the system, yet is often overlooked in favour of other technological challenges.

We are still many years away from the technology that will give such a capability, in a realistic size and at a reasonable cost, to every soldier, platform, or weapon on the future battlefield. It is not yet clear when we will get there and how much effort will be required, but the technology is progressing in that direction along several exciting fronts.

Chapter 7 – REFERENCES

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Annex A – SYMPOSIUM REVIEW

This annex reproduces portions of the review of the NATO RTO Symposium MP-SET-104 [2] written by Dr. Neil Barbour.

A.1 REVIEW OF MP-SET-104 SYMPOSIUM

A.1.1 Keynote Address

INS/GPS Technology Trends – Schmidt, G.T.

The keynote address ‘Future Navigation Systems: INS/GPS Technology Trends’ was presented by Dr. George Schmidt, USA. This address was an update of Dr. Schmidt’s keynote address at the SET-054 Symposium in 2002. Dr. Schmidt discussed the roadmap, originated in 1995, of technology trends towards improving accuracy, lowering cost, and reducing vulnerability. On inertial sensor trends it was stated that, even though the 3 cu in (50 cu cm), 1 deg/h INS/GPS, originally projected for 2006, has been delayed we are well on the way to meeting improved performance at lower cost and smaller size. MEMS IMUs are currently available, and in the very near term a 4 cu in (65 cu cm), 10 deg/h IMU will be commercially available. Further miniaturization of GPS receivers continues. Improved non-linear filtering techniques in which multiple GPS measurements are stored to update the INS have been developed. GPS accuracy has also continued to improve, with the integration of the NIMA and AF monitoring sites enabling improved updates to the GPS satellites. Within a year the entire GPS ground station upgrades will be complete, and it is expected that (without interference) INS/GPS systems will provide 1 meter navigation accuracy. In situations where GPS is jammed or periodically unavailable, deep integration has been shown to provide up to 15 dB improvement in Anti-Jam (A/J) capability. Deep integration is an optimum non-linear filter software implementation, so it is expected to be widely incorporated into military systems. MSpot remains on track to be implemented by about 2016, and this will provide another 15 – 20 dB improvement in A/J capability. In conclusion Dr Schmidt emphasized that to increase system robustness of military platforms, continued effort was required to: reduce cost and improve accuracy of the INS; improve receivers including deep integration; improve signals in space; and develop higher performance, lower cost adaptive antennas.

A.1.2 Topic 1 – Non-GNSS Systems and Concepts

Navigation in GNSS Denied Environments: Signals of Opportunity and Beacons – Duckworth, G.L. and Baranoski, E.J.

The first paper (Duckworth and Baranoski) provided a useful overview of the user needs and advantages and disadvantages of potential approaches (direct measurements, beacons, Signals Of Opportunity (SoOP)), inertial/dead reckoning, local environment disturbances/changes) to navigating in GNSS-denied environments. Reference was made to activities on ongoing DARPA programs in which the user could start navigating anywhere independent of the environment or any prior knowledge of it – highly important for military missions. Results were discussed on combating multi-path and exploitation of SoOP, using TV signals with a fielded system by Rosum Corporation. Exploitation of multi-path, rather than mitigation, showed future promise.

Tight Coupling of Laser Scanner and Inertial Measurements for a Fully Autonomous Relative Navigation Solution – Soloviev, A., Bates, D. and van Graas, F.

The second paper (Soloviev, Bates, van Graas) described a relative navigation solution for indoor and outdoor urban environments using a 2-D laser scanner and a tactical grade IMU. The laser scan relies on the availability of lines or surfaces from the surroundings to make relative measurements to update the IMU periodically. Position errors at the meter level were demonstrated after 200 meters of travel outdoors.

A Prototype Personal Navigation System – Soehren, W. and Hawkinson, W.

The next paper (Soehren and Hawkinson) presented Honeywell's prototype Personal Navigation System (PNS). System components include a MEMS IMU, 3-axis MEMS magnetometer, MEMS barometric pressure sensor, Selective Availability Anti-Spoofing Module (SAASM) GPS receiver, and innovative human -motion algorithms. Testing with GPS disabled for various time periods on the DARPA iPINS program showed that the system mostly met the goal of position error at <1% of distance traveled. Further studies showed that, in certain cases, terrain correlation may be a useful position aid.

Modelling and Simulation of a Map Aided Inertial Navigation Algorithm for Land Vehicles – Sönmez, T. and Bingöl, H.E.

Track Splitting Filtering Implementation for Terrain Aided Navigation – Ekütekin, V. and Özgören, M.K.

Papers four (Sonmez and Bingol) and six (Ekutekin) presented simulations of the application of Terrain Aided Navigation (TAN) in the absence of GPS. Sonmez and Bingol applied TAN to land vehicles; the advantage for land vehicles is that the height above the terrain is constant (i.e., zero clearance). While the results appear promising further study of the effects of terrain roughness and vehicle type are required. Ekutekin implemented Track Splitting Filtering (TSF) as a new TAN algorithm for a cruise missile navigation application. TSF has a lower probability of false fixes, but requires significantly longer calculation time.

Model-Based Processing for Simultaneous Mapping, Localization and Environmental Characterization in Underwater Environments – Cousins, D.B.

The fifth paper (Cousins) described a model-based investigation into fusing precision sonar sensing of the sea floor, including enhanced acoustic environment (sound speed) estimation, with INS measurements to improve both bathymetry and navigation performance. This is still in the early stages of modeling development.

Issues and Approaches for Navigation Using Signals of Opportunity – Raquet, J.F. and Miller, M.M.

The seventh paper (Raquet and Miller) discussed the benefits and drawbacks of navigation using signals of opportunity (SoOP) and identified typical SoOP system configurations. The presentation was quite tutorial in nature, and is a useful and fairly comprehensive reference.

Magnetometer Aided INS in Rolling Airframe Applications – Erer, K.S., Kayasal, U. and Semerci, B.

The last paper (Erer, Kaysal, Semerci) in this topic area described a magnetometer aided INS in a rolling airframe. Simulation and laboratory testing showed that the magnetometer aided INS had significant improvement over the INS alone. However, in practice the usual concerns remain about acquisition and interpretation of magnetic data, and susceptibility to magnetic disturbances.

A.1.3 Topic 2 – Sensors and Enabling Technologies

Small Inertial Navigation Sensors for GPS-Unavailable Environments – Barbour, N.M., Gustafson, D.E. and Hopkins II, R.E.

The first paper (Barbour, Gustafson, Hopkins) reviewed ongoing developments in small inertial sensor technology and simulated their use in random trajectory GPS-unavailable environments when augmented with a velocity meter. The ongoing developments are expected to provide relatively near term performance improvements in miniature FOGs and MEMS and possibly in the longer term with cold atom sensors. However, the simulations showed that only marginal improvements in position error would be gained, except in situations where the velocity meter has a low probability of providing accurate measurements.

MEMS Navigation-Grade Electro-Optical Accelerometer – Waters, R.L. and Jones, T.E.

The second paper (Waters and Jones) described a MEMS navigation grade accelerometer with a novel electro-optical displacement detection (readout) scheme comprising a Fabry-Perot cavity integrated with a photodiode. The device, which is in its third generation, provides very high scale factor and negligible cross-axis sensitivity and offers the potential for very high performance (~10 micro g).

Mode-Decoupled MEMS Gyroscopes with Silicon-On-Glass Technology – Alper, S.E. and Akin, T.

The next paper (Alper and Akin) discussed a MEMS gyroscope with improved drive and sense mode decoupling to minimize mechanical cross-talk, and hence quadrature coupling. Although there are several ways to compensate for quadrature or reduce it after build (e.g., laser trimming) the best approach is to minimize it through design as attempted in this paper. This gyro offers the potential for 10 deg/h performance or better.

MEMS Sensor and Integrated Navigation Technology for Precision Guidance – Sheard, K., Scaysbrook, I., Tidd, J., Faulk, N. and Cox D.

The fourth paper (Sheard *et al.*) described Atlantic Inertial Systems (formerly parts of BAe Systems) gun hard MEMS IMU/GPS Integrated Navigation System called the SiNAV02. The IMU is the SIIMU02, which uses the well known ring resonator MEMS gyroscope developed by BAE SYSTEMS. The SiIMU02 is in large scale production and the SiNav02 is undergoing customer air and gun launched firing trials. Stated performance is around 10 deg/h and 1 milli g, which makes it useful for a large number of military applications.

Precise Time Transfer Concepts – Dinh, S. and Stevens, I.

The fifth paper (Dinh and Stevens) presented an overview of precise time transfer concepts and discussed the operation principles of several time transfer methods currently implemented in military and commercial systems. This paper was tutorial in nature, but raised the important point that an absolute synchronization to a universal time reference is essential for military (and commercial) operations theater wide and world-wide. Currently GPS is the primary reference, but what will be the reference if GPS is unavailable?

Northrop Grumman's Family of Fiber-Optic Based Inertial Systems Enabling Precision Navigation and Geolocation – Tazartes, D., Johnnie, M., Song. I. and Volk, C.

The final paper in this section (Tazartes *et al.*) presented Northrop Grumman's family of fiber-optic based INSs which are highly reliable and widely used in military and commercial systems. FOG technology is

mature so system performance improvements are being developed using system advances such as transfer alignment techniques to reduce SAR targeting errors and differential GPS corrections to achieve sub-meter positional accuracies.

A.1.4 Topic 3 – Simulation and Testing

Analysis of Sensors and Techniques for the Design of a Robust Personal Navigator – Arden, D. and Bird, J.

The first paper (Arden and Bird) described test and analysis results conducted at DRDC-Ottawa towards determining an optimum sensor configuration for a robust personal navigator that would be most likely to provide precise position data in the absence of GPS. This effort is at the early development stage, so only very preliminary data were available and ongoing work to evaluate different configurations and integrated equipment needs to be completed. However, the effort is on the right track. An interesting finding while trying to characterize behavior with GPS data was that a modern commercial receiver performed better than a keyed military one.

Characterization of GPS Signals in Urban Environments Using Deeply Integrated GPS/IMU – Soloviev, A., Bruckner, D. and van Graas, F.

The second paper (Soloviev, Bruckner, van Graas) discussed GPS signal characterization in urban environments using a deeply integrated GPS/IMU. Measurements indicated that direct and indirect path signals from 5 or 6 satellites are available for processing even in dense urban canyons. The quality of the IMU was shown to affect carrier phase tracking capability thus allowing for 1 to 2 meter accuracy in relative position determination.

Testing Military Navigation Equipment – Fisher, D., Pottle, J. and Denjean, B.

The final paper (Fisher, Pottle, Denjean) presented techniques and benefits for testing military positioning and navigation systems under controlled laboratory conditions using simulation techniques. This paper was tutorial in nature, and gave a good outline of the benefits of simulating GNSS signals in an Embedded GPS Inertial (EGI) system with an RF generator (e.g., extend performance over and above flight test, insert controlled errors (interference and jamming), repeatability, security, low cost). Also, the actual IMU in the EGI system can be bypassed and position changes and errors simulated. GPS simulators for antenna testing are also available. These simulation techniques clearly are important during development and fielding of military systems.

A.1.5 Topic 4 – Military Systems and Applications

Alternative Display and Directional Modalities in Support of Soldier Way-Finding – Bossi, L.L.M., Frim, J. and Tack, D.W.

Visual, Auditory and Tactile Navigational Information Presentation Modalities in Support of Soldier Wayfinding – Frim, J., Bossi, L.L.M. and Tack, D.W.

The first two papers (Bossi, Tack, Frim) and (Frim, Bossi, Tack) presented findings from soldier tests using an improved navigation device (GPS receiver, magnetic compass, laptop computer, stored maps) developed from the Soldier Information Requirements Technology Demonstration (SIREQ TD) in support of soldier wayfinding. The first paper covered the pros and cons of alternative display and directional modalities for soldiers traversing wooded terrain over pre-planned routes while receiving either visual, auditory, or tactile

cues in 1-D or 2-D. The second paper discussed alternate and improved ways the navigation information cues were presented to the soldier individually and in platoon formation. In all cases navigation was improved over the standard method, but soldier feedback showed distinct preferences. This highlights the importance of keeping the user, as well as the mission, in mind when developing new equipment.

A Novel Tactical Artillery Surveying and Gun Laying System Family, TARSUS – Eren, M., Atesoglu, O. and Guner, D.R.L.

The third paper (Eren, Atesoglu, Guner) described ASELSAN Inc's family of new generation Tactical Artillery Surveying and gun laying Systems (TARSUS). TARSUS integrates a GPS/odometer aided INS and an angle/distance measuring theodolite to produce a family of systems that are highly accurate and faster than current ones. Artillery survey teams still have a very important role to provide timely and accurate position and azimuth information for ground-based fire support to military elements, so this is a useful product.

Aided-Inertial GPS-Denied Navigation and Mapping – Lithopoulos, E.

The fourth paper (Lithopoulos, Lalumiere, Beyeler) described the basic design, operation and future development of Applanix Corporations GPS-denied navigation and mapping system. The system is vest mounted and, after alignment, navigates based on measurements of motion dynamics with periodic ZUPTs. For high accuracy indoor navigation a prototype mapping system with an eleven sensor camera was described. Navigation with facility maps is a very important capability for determining precise in-building locations for military and first responders.

Cooperative Blue-Force Tracking (BFT) and Shared Situation Awareness (SA) in Complex Terrains – Labbé, P., Lamont, L., Ge, Y. and Arden, D.

The final paper (Labbé, Lamant, Ge, Arden) discussed how adaptive networks can be used to build up a map of the relative locations of mobile and stationary units to improve cooperative Blue Force Tracking (BFT) and shared Situational Awareness (SA) in complex terrains. The paper explored the potential synergy by integrating technologies such that the probability of failure in one will have minimal effect on the overall performance. The conclusion drawn is that the approach supports the hypothesis of improved shared SA and BFT, but that more research and development is required to make this complicated problem a practicality.

A.1.6 Topic 5 – Robust GNSS Integration Techniques

Sensor Fusion for Robust Urban Navigation: Test Results from the Advanced Position/Navigation and Tracking the Future Force (APNTFF) Program – Olson, P.M., Sokolowski, S., Vo, N., Fax, A. and Berardi, S.

The first paper (Olson *et al.*) described test results from an integrated sensor suite developed under the US Army's Advanced Navigation and Tracking the Future Force program. The sensor suite comprised a MEMS IMU, soldier motion detector, RF ranging, and network assisted GPS packaged in a backpack. Promising results were demonstrated with sensor fusion using correct step modeling and screens to detect false measurements. Indoor and outdoor position error was within 6 – 8 meters over various test conditions and gaits. The sensor suite appears to be compatible with future packaging in a form factor that might meet Army requirements for (dismounted) soldiers.

Integrated Navigation System Using Sigma-Point Kalman Filter and Particle Filter – Sotak, M., Sopata, M. and Berezny, S.

The second paper (Sotak, Sopata, Berezny) compared the advantages of Sigma-Point Kalman filters (SPKF) and Particle Filters (PF) over traditional Kalman filters (such as linearized and extended) for merging information in an integrated INS/GPS. Both the SPKF and PF are approximate non-linear estimation techniques expected to improve performance over traditional extended Kalman filters for various applications at the price of increased complexity and computational requirements. It is not clear what improvements will be achieved when compared with a complete optimal non-linear filter such as is implemented in “deep integration” of a GPS and INS.

Enhanced Tracking Performance Using Ultra-Tightly Coupled GPS/INS Techniques – Lewis, D.E.

The third paper (Lewis) discussed enhanced tracking performance using ultra-tightly coupled GPS/INS. Two IMUs (a Ring Laser Gyro (RLG) IMU (<1 deg/h) and a MEMS IMU (30 deg/h)) as well as two clocks (TCXO and OCXO) were integrated with a GPS receiver. For all configurations the improvement with ultra-tightly coupled ranged from 5 – 15 dB. Clock performance appeared to be more critical than IMU performance and this should be evaluated further.

Recent Advances in Accuracy Enhancement of MEMS-Based IMUs for Navigation Applications – Noureldin, A., Eberts, M., Johnston, C., El-Sheimy, N. and Bird, J.

The fourth paper (Noureldin *et al.*) presented analyses and results from techniques for accuracy enhancement of MEMS-based IMUs, namely the impact of de-noising (pre-filtering) MEMS sensor output, a segmented Kalman filter, closed loop IMU/GPS, and stochastic modeling of MEMS inertial sensor errors. Potential for improving MEMS INS/GPS navigation performance was demonstrated. Although improving MEMS navigation performance is important, it was not clear whether significant improvement will actually be accomplished for military MEMS with these techniques.

Ultra-Tight GPS/INS for Carrier Phase Positioning in Weak-Signal Environments – Petovello, M.G., O’Driscoll, C. and Lachapelle, G.

The final paper (Petovello, O’Driscoll, Lachapelle) discussed the benefits of using an ultra-tightly integrated GPS/INS to extend the carrier phase tracking capability and hence improve Real-Time Kinematic (RTK) positioning accuracy. Results from a pedestrian-based field test showed that the ultra-tight integrated receiver had ~7 dB sensitivity improvement over a standard one. This study was performed in an open sky environment with simulated GPS signal attenuation. Further work in a real environment is required.

A.2 CONCLUSIONS AND RECOMMENDATIONS

The Symposium achieved its purpose of bringing together leading experts in the field of navigation sensors and integration technology to present emerging system concepts to the NATO community. The Program Committee and the Turkish National hosts are to be congratulated for their efforts in arranging this technical symposium. The topics covered a broad range of activities for navigation in GPS-unavailable environments and provided substantial information to the community.

Enabling technologies presented in the Symposium indicated that, while there are continuing advances in navigation sensors, most of the effort is being spent on sensor integration and algorithmic and software development . This is to be expected because the desire to use low cost, small size and hence limited accuracy

(around 1 deg/h) INSs drives the need for the integration of a large number of other sensors to aid/augment the INS for accurate position determination. Furthermore, military applications are continuing to expand the role of navigation beyond the basic ‘where am I going and how do I get there’ to include situational awareness, interoperability, cooperative navigation, and the impacts of command and control possibly from remote sites. Ability to operate in these modes is essential for NATO forces of the future. However, the information presented in the Symposium indicated that these emerging military capabilities are still several years away.

GPS-unavailable navigation is a difficult problem and many of the papers described results from simulations and tests that were in the early development stages. It was thus difficult to determine which technologies may be the most promising. However, clear enabling technology advances were reported in the following areas: significantly improved GPS A/J capability by 2016; prototype Personal Navigation Systems (PNSs); sensor fusion/integration; MEMS IMUs and sensors; FOG systems; GNSS simulation hardware; artillery surveying and gun laying; and improved robustness. A very high level of interoperability in the future combat system between soldiers and soldier groups and the surrounding platforms is expected starting around 2010. NATO personnel must be ready to incorporate these technology advances into their training and operational activities.

Nearly all of the Personal Navigation Systems (PNSs) presented are currently packaged in backpacks and are too cumbersome, too heavy, and not consistently accurate enough for the soldier in the field to use. Even with the expected availability of a 4 cu in (65 cu cm) MEMS IMU in the very near term, a significant size and power reduction for a wearable, accurate PNS will require MEMS-like packaging of all components. Typical goals have been set at 4 – 10 cu in, 1 – 3 lbs, less than 5 W power, and with position knowledge of 1 – 3 meters. Rapid initialization of the system is also a problem. NATO personnel should be involved in testing, evaluating, and providing feedback on these systems.

It is clear that much effort and investment will continue to be spent on improving navigation in GPS-unavailable situations, and that this is a rapidly moving field. **The SET Panel should maintain expertise on the Panel in this area and should review progress in another 3 – 5 years by holding a similar Symposium.** Some of the current presenters might be requested to provide an update of their technology developments. In particular the next symposium could be broadened to provide sessions on the enabling technologies identified herein, such as: precise timing concepts; miniature integrated PNSs; accurate, very low power, small sensors (e.g., inertial and augmentation); signals of opportunity; targeting and mapping. Papers should be encouraged to emphasize recent tests results rather than academic analyses.

Annex B – INS/GPS TECHNOLOGY TRENDS (G. SCHMIDT)

The following paper was presented at the Lecture Series and was published as part of RTO-EN-SET-116 [1]. It is included here in its entirety.

INS/GPS Technology Trends

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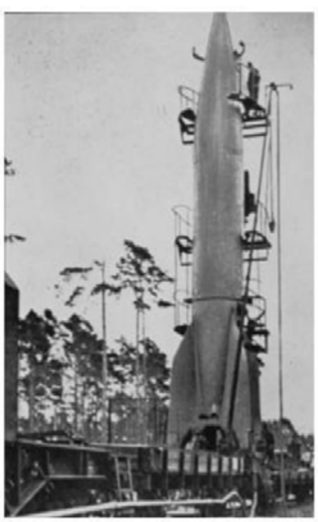
Abstract

This paper focuses on accuracy and other technology trends for inertial sensors, Global Positioning Systems (GPS), and integrated Inertial Navigation System (INS)/GPS systems, including considerations of interference, that will lead to better than 1 meter accuracy navigation systems of the future. For inertial sensors, trend-setting sensor technologies will be described. A vision of the inertial sensor instrument field and inertial systems for the future is given. Planned accuracy improvements for GPS are described. The trend toward deeply integrated INS/GPS is described, and the synergistic benefits are explored. Some examples of the effects of interference are described, and expected technology trends to improve system robustness are presented.

1.0 Introduction

During the last 60 years, INSs have progressed from the crude electromechanical devices that guided the early V-2 rockets (Figure 1a) to the current solid-state devices that are in many modern vehicles. The impetus for this significant progress came during the ballistic missile programs of the 1960s, in which the need for high accuracy at ranges of thousands of kilometers using autonomous navigation systems was apparent. By "autonomous" it is meant that no man-made signals from outside the vehicle are required to perform navigation. If no external man-made signals are required, then an enemy cannot jam them.

One of the early leaders in inertial navigation was the Massachusetts Institute of Technology (MIT) Instrumentation Laboratory (now Draper Laboratory), which was asked by the Air Force to develop inertial systems for the Thor and Titan missiles and by the Navy to develop an inertial system for the Polaris missile. This request was made after the Laboratory had demonstrated in 1953 the feasibility of autonomous all-inertial navigation for aircraft in a series of flight tests with a system called SPIRE (Space Inertial Reference Equipment), Figure 1b. This system was 5 ft in diameter and weighed 2700 lb. The notable success of those early programs led to further application in aircraft, ships, missiles, and spacecraft such that inertial systems are now almost standard equipment in military and civilian navigation applications.



Inertial navigation systems do not indicate position perfectly because of errors in components (the gyroscopes and accelerometers) and errors in the model of the gravity field that the INS implements. Those errors cause the error in indicated position to grow with time. For vehicles with short flight times, such errors might be acceptable. For longer-duration missions, it is usually necessary to provide periodic updates to the navigation system such that the errors caused by the inertial system are reset as close to zero as possible. Because GPS offers world-wide, highly accurate position information at very low cost, it has rapidly become the primary aid to be used in updating inertial systems, at the penalty of using an aid that is vulnerable to interference. Clearly, the ideal situation would be low-cost but highly accurate INS that can do all, or almost all, of the mission without using GPS.

The military has had access to a specified accuracy of 21 m (95-percent probability) from the GPS Precise Positioning Service (PPS). This capability provides impressive worldwide navigation performance, especially when multiple GPS measurements are combined in a Kalman filter to update an INS on a military platform or a weapon. The Kalman filter provides an opportunity to calibrate some of the GPS errors, such as satellite clock and ephemeris errors, as well as several of the inertial system errors, and when properly implemented, Circular Error Probables (CEPs) better than 5m have been observed. In the near term, accuracies in the integrated navigation solution are predicted to improve to the 1 meter level. These accuracies will need to be available in the face of intentional interference of GPS, and the inertial system will provide autonomous navigation information during periods of GPS outage.

The following sections describe:

- The expected technology trends for inertial sensors and systems that can support autonomous operation at low cost. Expectations are for INS/GPS systems that are smaller than 3 in^3 and weigh less than a pound, and cost under $1000.
- Expected accuracy improvements and implementations for GPS.
- Issues and benefits of INS/GPS integration, particularly in an environment with interference.

The combination of a robust, antijam GPS receiver and an accurate, low-cost inertial system will provide the global precision navigation system of the future. Figure 2 depicts the "roadmap" to meeting this objective.

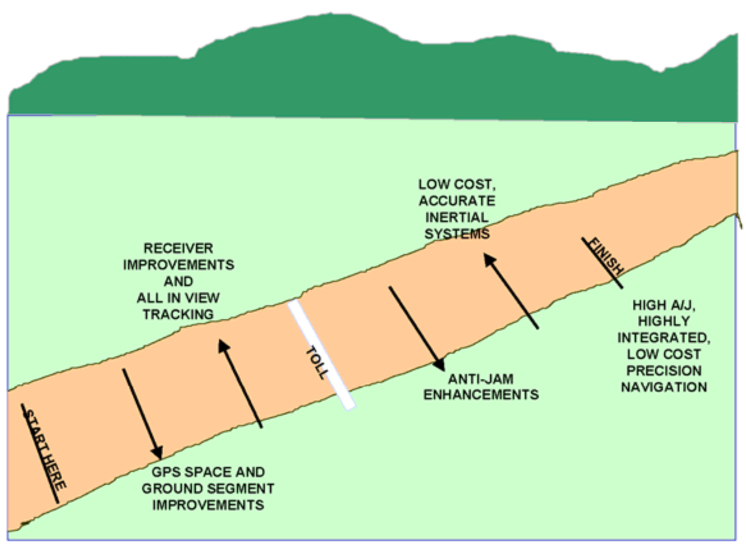


Figure 2. Roadmap to precision navigation for multiple applications.

2.0 Inertial Sensor Trends

The major error sources in the inertial navigation system are due to gyro and accelerometer inertial sensor imperfections, incorrect navigation system initialization, and imperfections in the gravity model used in the computations. But, in nearly all inertial navigation systems, the largest errors are due to the inertial sensors.

Whether the inertial sensor error is caused by internal mechanical imperfections, electronics errors, or other sources, the effect is to cause errors in the indicated outputs of these devices. For the gyros, the major errors are in measuring angular rates. For the accelerometers, the major errors are in measuring acceleration. For both instruments, the largest errors are usually a bias instability (measured in deg/hr for gyro bias drift, or micro g (μg) for the accelerometer bias), and scale-factor stability (which is usually measured in parts per million (ppm) of the sensed inertial quantity). The smaller the inertial sensor errors, the better the quality of the instruments, the improved accuracy of the resulting navigation solution, and the higher the cost of the system. As a "rule-of-thumb," an inertial navigation system equipped with gyros whose bias stability is 0.01 deg/hr will see its navigation error grow at a rate of 1 nmi/hr of operation. The navigation performance requirements placed on the navigation system lead directly to the selection of specific inertial instruments in order to meet the mission requirements.

Figure 3, "Current Gyro Technology Applications," gives a comprehensive view of the gyro bias and scale-factor stability requirements for various mission applications and what type of gyro is likely to be used in current applications (Figures 3 – 9 are revised versions of the figures in Ref. [1]).

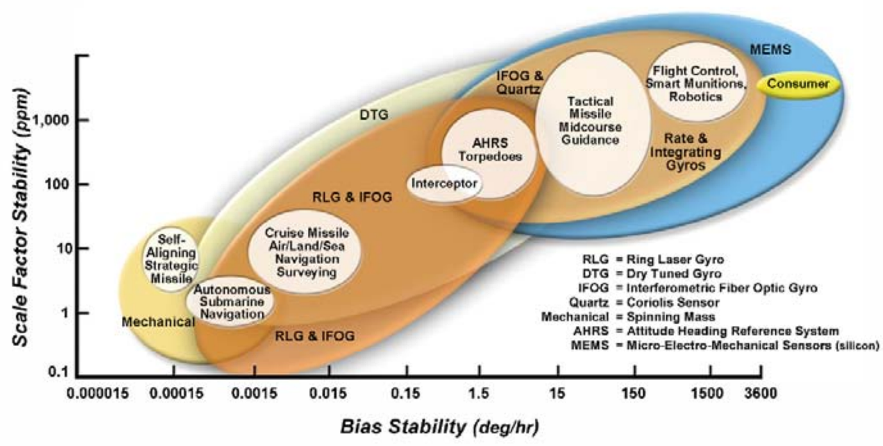


Figure 3. Current gyro technology applications.

Solid-state inertial sensors, such as Microelectromechanical System (MEMS) devices, have potentially significant cost, size, and weight advantages, which has resulted in a proliferation of the applications where such devices can be used in systems. While there are many conventional military applications, there are also many newer applications that will emerge with the low cost and very small size inherent in such sensors, particularly at the lower performance end of the spectrum. A vision of the gyro inertial instrument field for relevant military applications for the near-term (10 years) is shown in Figure 4.

The MEMS and Interferometric Fiber-Optic (IFOG) technologies are expected to replace many of the current systems using Ring Laser Gyros (RLGs) and mechanical instruments. However, one particular area where the RLG is expected to retain its superiority over the IFOG is in applications requiring extremely high scale-

factor stability. The change to all-MEMS technology hinges primarily on MEMS gyro development. The performance of MEMS instruments is continually improving, and they are currently being developed for many applications. This low cost can only be attained by leveraging off the consumer industry, which will provide the infrastructure for supplying the MEMS sensors in extremely large quantities (millions). The use of these techniques will result in low-cost, high-reliability, small-size, and lightweight inertial sensors and the systems into which they are integrated. The tactical (lower) performance end of the application spectrum will likely be dominated by micromechanical inertial sensors. The military market will push the development of these sensors for applications such as "competent" and "smart" munitions, aircraft and missile autopilots, short-time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, "smart skins" using embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale INS/GPS systems.

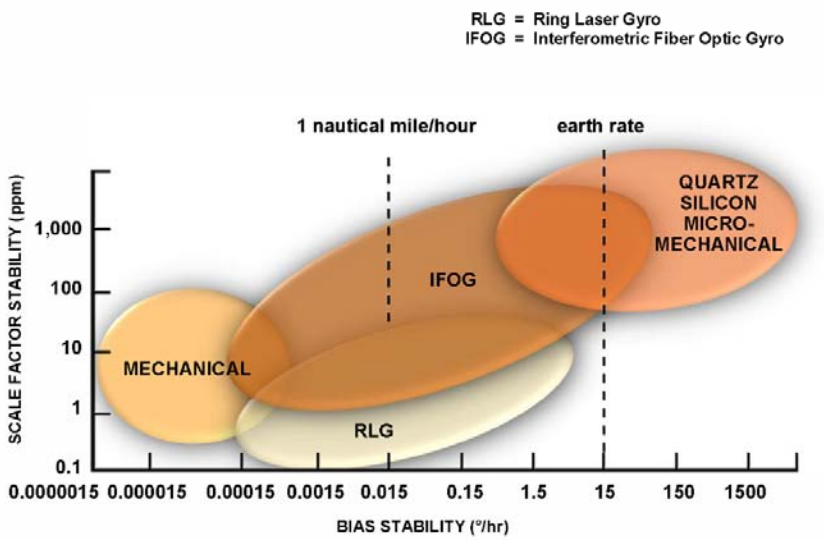


Figure 4. Near-term gyro technology applications.

Figure 5 shows how the gyro technology may be applied to new applications in the far term, somewhere around 2020. The figure shows that the MEMS and integrated-optics (IO) systems technology will dominate the entire low- and medium-performance range. The rationale behind this projection is based on two premises. The first is that gains in performance in the MEMS devices will continue with similar progression to the dramatic 3 to 4 orders-of-magnitude improvement that has already been accomplished in the last decade. That further improvements are likely is not unreasonable since the designers are beginning to understand the effects of geometry, size, electronics, and packaging on performance and reliability. Second, efforts are already underway to put all six sensors on one (or two) chips, which is the only way to reach a possible cost goal of less than \$1000 per INS/GPS system. In addition, since many of the MEMS devices are vibrating structures with a capacitive readout, this may restrict the performance gains. It is in this area that the integrated optics technology is most likely to be required to provide a true solid-state micromechanical gyro with optical readout. At this time, the technology to make a very small, accurate gyro does not exist, but advances in integrated optics are already under development in the communications industry. For the strategic application, the IFOG could become the dominant gyro. Work is underway now to develop radiation-hard IFOGs as well as super-high-performance IFOGs.

A potentially promising technology, which is in its infancy stages, is inertial sensing based upon atom interferometry (sometimes known as cold atom sensors). A typical atom de Broglie wavelength is 30,000 times smaller than an optical wavelength, and because atoms have mass and internal structure, atom interferometers are extremely sensitive. Accelerations, rotations, electromagnetic fields, and interactions with other atoms change the atom interferometric fringes. In theory, this means that atom interferometers could make the most accurate gyroscopes, accelerometers, gravity gradiometers, and precision clocks, by orders of magnitude. If this far-term technology can be developed, then it could result in a 5-meter/hour navigation system without GPS, in which the accelerometers are also measuring gravity gradients.

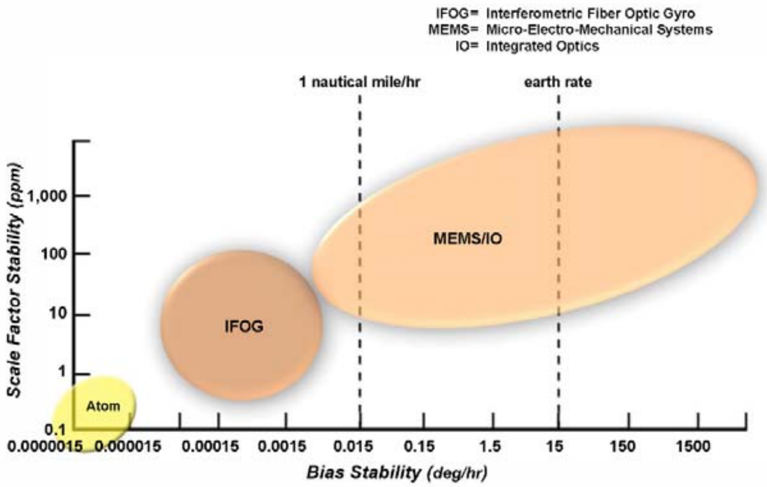


Figure 5. Far-term gyro technology applications.

Figure 6, "Current Accelerometer Technology Applications," gives a comprehensive view of the accelerometer bias and scale-factor stability requirements for various mission applications and what type of accelerometer is likely to be used in current applications. "Mechanical Instruments" refers to the use of a Pendulous Integrating Gyro Assembly (PIGA) which is a mass unbalanced spinning gyroscope used to measure specific force.

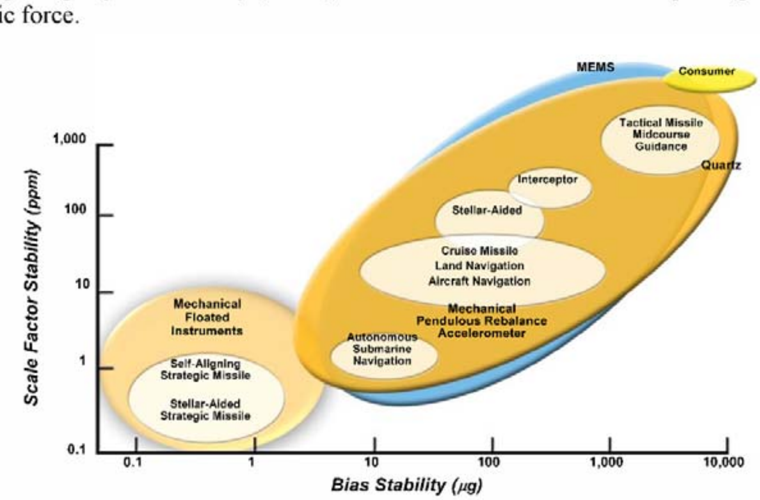


Figure 6. Current accelerometer technology applications.

Current applications are still dominated by electromechanical sensors, not only because they are generally low-cost for the performance required, but also because no challenging alternative technology has succeeded, except for quartz resonators, which are used in the lower-grade tactical and commercial applications. MEMS inertial sensors have not yet seriously broached the market, although they are on the verge of so doing, especially in consumer applications.

In the near-term (Figure 7), it is expected that the tactical (lower) performance end of the accelerometer application spectrum will be dominated by micromechanical accelerometers. As in the case for gyros, the military market will push the development of these sensors for applications such as "competent" and "smart" munitions, aircraft and missile autopilots, short-time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, "smart skins" using embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale INS/GPS systems. Higher performance applications will continue to use mechanical accelerometers and possibly resonant accelerometers based on quartz or silicon. Quartz resonant accelerometers have proliferated widely into tactical and commercial (e.g., factory automation) applications. Silicon micromechanical resonator accelerometers are also being developed. Both of these technologies have possible performance improvements.

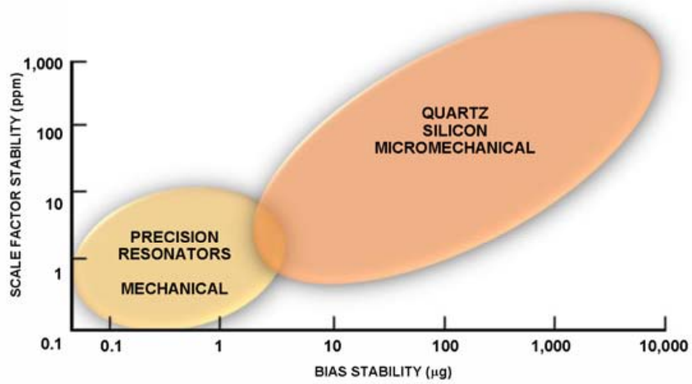


Figure 7. Near-term accelerometer technology applications.

Figure 8 shows how the accelerometer technology may be applied to new applications in the far term. As in the case of gyro projections for the future, the figure shows that the MEMS and integrated optics technology will dominate the entire low- and medium-performance range. The rationale behind this projection is based on exactly the same two premises as for the gyros. However, it is likely that the far-term accelerometer technology projections will be realized years sooner than the gyro.

Figure 9 shows INS or INS/GPS relative system cost "projections" as a function of inertial instrument technology and performance. The cost of a GPS receiver is likely to be so small that it will be insignificant. The systems are classified as: laser gyro or IFOG systems containing various types of accelerometer technologies; quartz systems with both quartz gyros and quartz accelerometers; and MEMS/integrated optics systems. The solid line indicates the range of approximate costs expected. Clearly, the quantity of systems produced affects the cost; large production quantities would be at the lower end of the cost range. The IFOG systems have the potential for lower cost than laser gyro systems because the IFOG should be well below the cost of an RLG. However, this has not happened to date, primarily because the RLG is in relatively large-volume production in well-facilitated factories and the IFOG is not yet manufactured in similar production quantities. Clearly, the MEMS/integrated optics INS/GPS systems offer the lowest cost. The ultimate low cost only becomes feasible in quantities of millions. This can be achieved only with multi-axis instrument clusters and on-chip or adjacent-chip electronics and batch packaging.

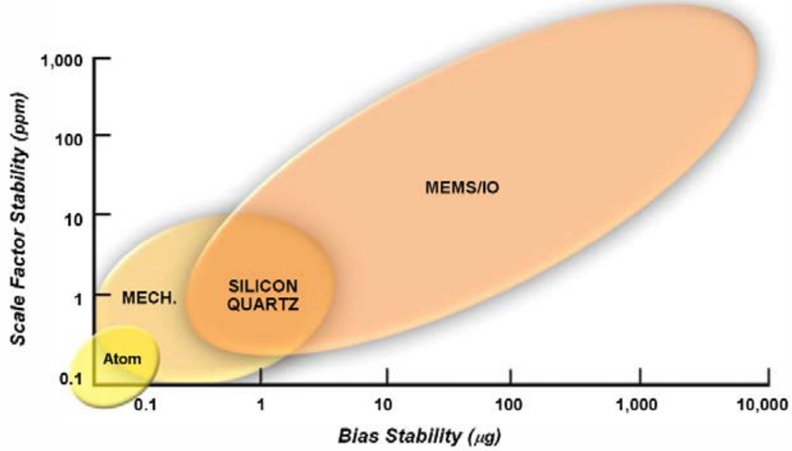


Figure 8. Far-term accelerometer technology applications.

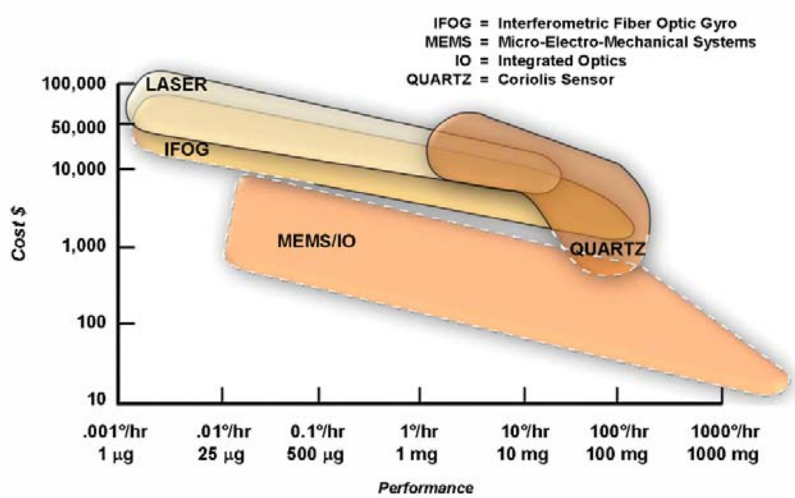


Figure 9. INS cost as a function of instrument technology.

The ability of silicon-based MEMS devices to withstand high "g" forces has been demonstrated recently in a series of firings in artillery shells where the g forces reached over 6500 g. These small MEMS-based systems, illustrated in Figure 10, have provided proof-of-principal that highly integrated INS/GPS systems can be developed and led to a recent program where the goal was a system on the order of 3 in^3, or 2 in^3 for the INS alone (Ref. [2]). Unfortunately, the goals have not yet been met. The current status (2007) of a MEMS INS is represented by the Honeywell HG1900 with a weight <1 lb., volume 17.25 cubic inches, power <1.95 watts, gyro bias of 3 °/hr, and gyro angle random walk of 0.09 $^{\circ}/\sqrt{hr}$. This system is in low rate production. Entering production in the near future is the HG1930 which has a volume of 4 cubic inches, a gyro bias of 10 ^{0}/hr and a gyro random walk of 0.12 deg/$\sqrt{hr}$ (Ref. [3]. The volumes compare with tactical grade RLG and IFOG systems with a volume of about 34in^3. These systems also represent 4 orders of magnitude improvement in weight and volume over SPIRE. If micromechanical instrument performance improvements can be made, they will come to dominate the entire inertial instrument application spectrum.

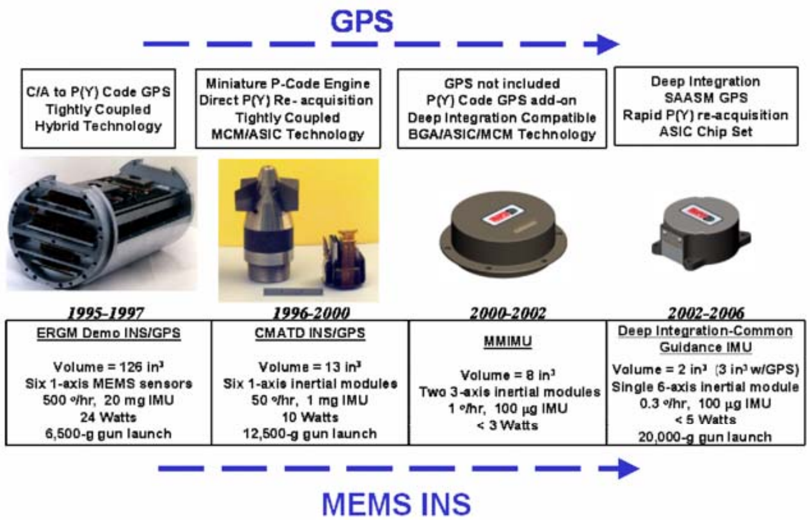


Figure 10. INS/GPS guidance system evolution.

3.0 GPS Accuracy and Other Improvements

The accuracy specification that is currently applicable to the GPS results in a precise positioning (PPS) of a GPS receiver operating with the military P(Y) code of approximately 10 m (CEP) in the WGS-84 coordinate system. Recent advances and programs to improve GPS accuracy have contributed to the real possibility of developing INS/GPS systems with smaller than 1-m CEP in the near term. This section will discuss these items.

The accuracy of the GPS PPS provides impressive navigation performance, especially when multiple GPS measurements are combined in a Kalman filter to update an INS. The Kalman filter provides an opportunity to calibrate the GPS errors, as well as the inertial errors, and when properly implemented, CEPs better than either system are achievable.

In assessing GPS accuracy in the mid 1990's, the largest error sources were in the space and control segment. The space segment dominant errors are: ionospheric errors, tropospheric errors, satellite clock errors, and satellite ephemeris with the latter two errors being dominant. The ionospheric errors can be reduced by using a two-frequency receiver (L_1 and L_2) and tropospheric errors can be reduced by using a deterministic compensation model. Table 1 gives a typical 1995 absolute GPS error budget (Ref. [4], p. 105). Horizontal Dilution of Precision (HDOP) is a geometrical factor that is a function of the geometry between the GPS receiver and the tracked satellites. For tracking four satellites, HDOP is typically 1.5. Then with a user equivalent range error (UERE) of 3.8m, and applying the approximate formula, CEP = (0.83) (HDOP) (UERE), the resulting CEP is 4.7 m.

Table 1. "Typical" absolute GPS error budget. (circa 1995)

GPS Noise-Like Range Errors	1σ Values (m)
Multipath	0.6
Receiver noise	0.3
RMS noise-like error	0.7
GPS Bias-Like Range Errors	**1σ Values (m)**
Satellite ephemeris	1.4
Satellite clock	3.4
Atmospheric residual	0.2
RMS bias-like error	3.7

User equivalent range error (UERE) = $(0.7^2 + 3.7^2)^{1/2}$=3.8m

CEP = (0.83) (UERE) (HDOP) = 4.7m if HDOP = 1.5

Beginning in the mid 1990's various accuracy improvement programs were begun (Refs. [4] – [7]) to reduce the clock and ephemeris errors listed in Table 1. These errors can be reduced by sending more accurate and more frequent ephemeris and clock updates to the satellites from the control segment. In addition, if pseudorange corrections for all satellites are uploaded in each scheduled, individual satellite upload, then a PPS receiver can decode the messages from all satellites it is tracking and apply the most recent correction set. Increasing the upload frequency to three uploads per day for each satellite is expected to improve the combined error contribution of clock and ephemeris for PPS users by 50% by substantially decreasing the average latency of 11.5 hours in the data broadcast by the satellites.

In another phase of the program called the Accuracy Improvement Initiatives, the data from six National Geospatial Agency (NGA) GPS monitoring sites were integrated with data from the six existing Air Force monitoring sites in the operational control segment (OCS). By including additional data from the NGA sites, which are located at higher latitudes than the Air Force sites, an additional 15-percent improvement in combined clock and ephemeris accuracy is predicted. Improvements to the Kalman filter that is used in the ground control segment to process all the satellite tracking information can further reduce the errors by 15 percent. In addition, by incorporating better dynamical models in the filter, another 5-percent improvement may be anticipated. Table 2 summarizes these predicted accuracy improvements (Ref. [4], p. 102).

Table 2. Planned reduction of combined clock and ephemeris errors.

Enhancement	Anticipated Combined Clock and Ephemeris Error Improvement over Existing Combined Error of 3.7 m (1σ)
Correction Updates (50% reduction)	1.8 m
Additional Monitor Stations (additional 15% reduction)	1.5 m
Non partitioned Kalman Filter (additional 15% reduction)	1.3 m
Improved Dynamic Model (additional 5% reduction)	1.2 m

Figure 11 shows the additional six NGA sites added in the initial stages of the Accuracy Improvement Initiative. The final five NGA sites included were at even higher latitudes to provide even more tracking data and additionally provide triple ground station usability of every GPS satellite.

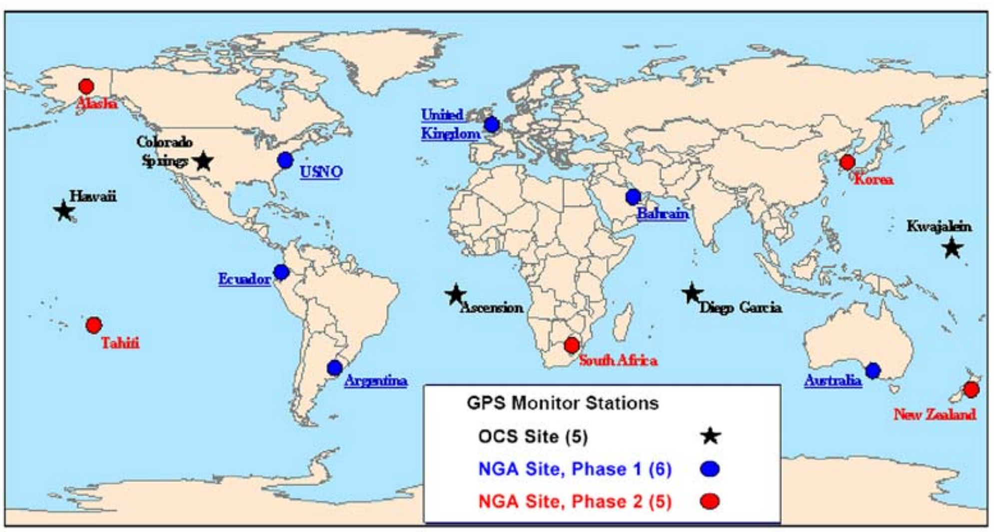


Figure 11. OCS and NGA Tracking Stations

Improvements in the GPS Master Station Control Segment software such as implementing a non-partitioned Kalman filter and improved dynamic models are presented in Figure 12.

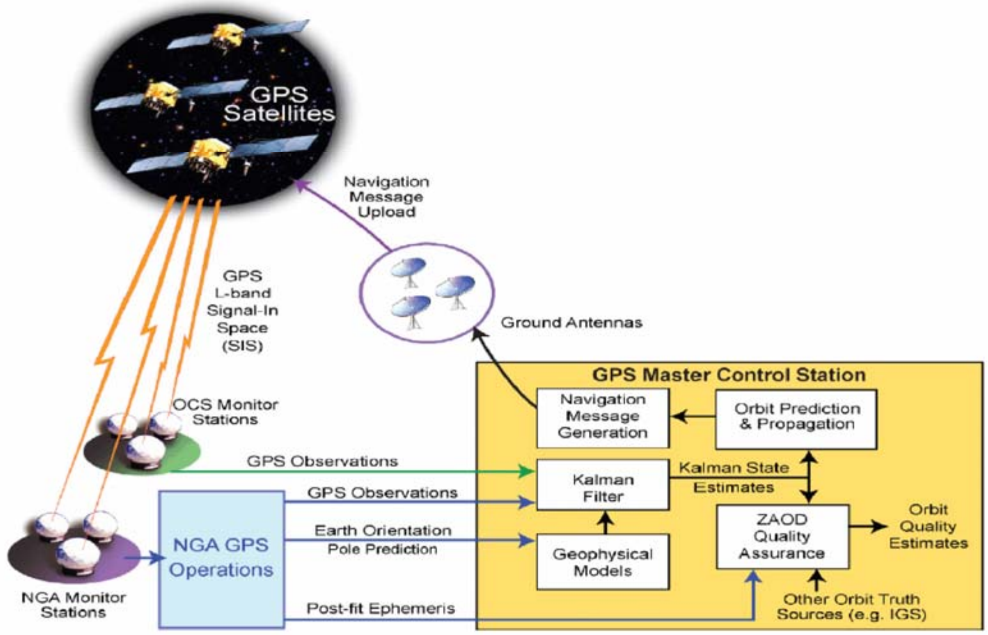


Figure 12. OCS Data Flow After Implementation of Accuracy Improvements

After all of these improvements, a ranging error on the order of 1.4 m is a reasonable possibility with the atmospheric residual unchanged. With all-in-view tracking (HDOP approximately 1.0), CEPs on the order of 1 m appear quite possible in the near term. CEP=(0.83) (1.0) (1.4) = 1.1 m. If then, multiple GPS measurements are combined with an inertial system and Kalman Filter, better than 1 m accuracy should result.

To illustrate the benefits of the various GPS improvements, a simulation was conducted with an error model for a typical INS whose errors would result in 1.0 nmi/h error growth rate without GPS aiding. After 30 minutes of air vehicle flight including GPS updates every second, with all of the GPS accuracy improvements included, less than 1 meter CEP is obtained as shown in Table 3.

Table 3. Tightly coupled INS/GPS System-Air Vehicle Trajectory (@30 min).

CLOCK AND EPHEMERIS ERROR (1σ) ALL IN VIEW TRACKING	CEP (m) 8 SATELLITES
Current Model – 3.7 m	2.97 m
Correction Updates – 1.8 m	1.46 m
Additional Monitor Stations – 1.5 m	1.22 m
Non-partitioned Kalman Filter – 1.3 m	1.06 m
Improved Dynamic Model – 1.2 m	0.98 m

Another significant improvement in GPS for military systems will be the introduction of the M-code in GPS III, which is designed to be more secure and have better jamming resistance than the current Y code (Ref. [7]). The system is being designed such that a higher power signal (+20 dB over current signal levels) will be available for localized coverage over an area of operations to boost signal jamming resistance. This significant improvement (M-code spot beam) is scheduled for the GPS-III phase of the GPS modernization process.

4.0 INS/GPS Integration

Many military inertial navigation systems could be replaced with less accurate inertial systems if it were guaranteed that GPS would be continuously available to update the inertial system to limit its error growth. A less accurate inertial system usually means a less costly system. However, given the uncertainty in the continuous availability of GPS in most military scenarios, an alternate way to reduce the avionics system cost is to attack the cost issue directly by developing lower-cost inertial sensors while improving their accuracy and low noise levels, as described in the "Inertial Sensor Trends" section. For applications without an interference threat, in the future, GPS updating is expected to provide better than 1-m navigation accuracy (CEP) when used in conjunction with an INS. The benefits and issues in using INS augmented with GPS updates, including a discussion of interference issues, have been presented in many references. Systems currently in use tend to be classified as either "the loosely coupled approach" or "the tightly coupled approach" (Figures 13 and 14 and Ref. [8]).

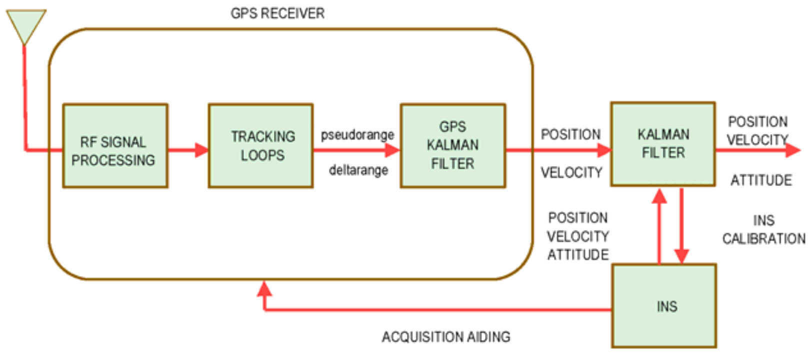


Figure 13. Loosely coupled approach.

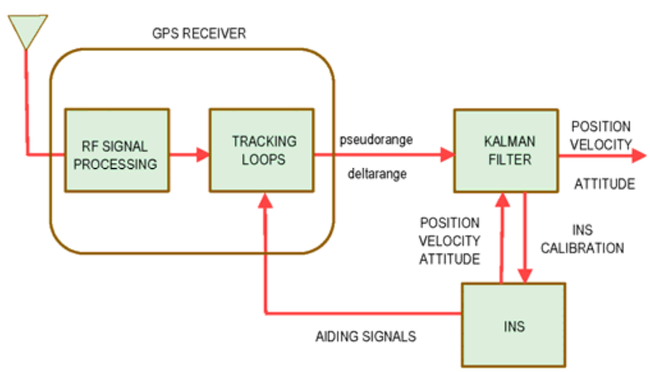


Figure 14. Tightly coupled approach.

The most recent research activity is a different approach called "deeply integrated" (Figure 15, Refs. ([9] and [10]). In this approach, the problem is formulated directly as a navigation problem in which the optimum (minimum-variance) solution is sought for each component of the multidimensional navigation state vector. By formulating the problem in this manner, the navigation algorithms are derived directly from the assumed dynamical models, measurement models, and noise models. The solutions that are obtained are not based on the usual notions of tracking loops and operational modes (e.g., State 3, State 5, etc.). Rather, the solution employs a nonlinear filter that operates efficiently at all jammer/signal (J/S) levels and is a significant departure from traditional extended Kalman filter designs. The navigator includes adaptive algorithms for estimating postcorrelation signal and noise power using the full correlator bank. Filter gains continuously adapt to changes in the J/S environment, and the error covariance propagation is driven directly by measurements to enhance robustness under high jamming conditions.

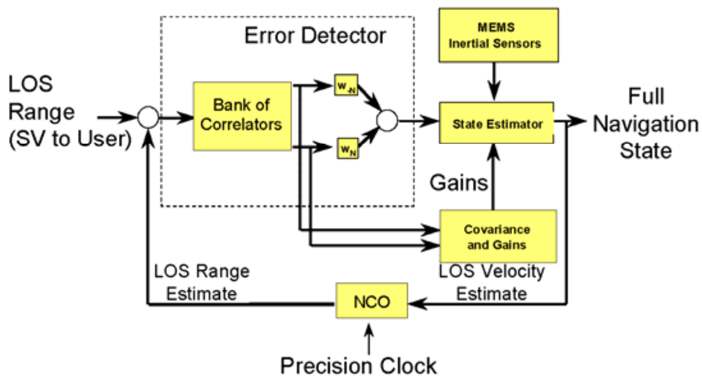


Figure 15. INS/GPS deep integration.

In this system, individual satellite phase detectors and tracking loop filters are eliminated. Measurements from all available satellites are processed sequentially and independently, and correlation among the line-of-sight distances to all satellites in view is fully accounted for. This minimizes problems associated with unmodeled satellite signal or ephemeris variations and allows for full Receiver Autonomous Integrity Monitoring (RAIM) capability.

Extended-range correlation may be included optionally to increase the code tracking loss-of-lock threshold under high jamming and high dynamic scenarios. If excessively high jamming levels are encountered (e.g., beyond 80 dB J/S at the receiver input for P(Y) code tracking), the GPS measurements may become so noisy that optimal weights given to the GPS measurements become negligible. In this situation, navigation error behavior is essentially governed by current velocity errors and the characteristics of any additional navigation sensors that are employed, such as an INS. Code tracking is maintained as long as the line-of-sight delay error remains within the maximum allowed by the correlator bank. If there is a subsequent reduction in J/S so that the optimal weights become significant, optimum code tracking performance is maintained without the need for reacquisition. Detector shapes for each correlator depend on the correlator lag and rms line-of-sight delay error.

Experiments have shown an improvement in code tracking of about 10 to 15 dB in wideband A/J capability for this architecture. Another 5 dB might be possible with data stripping to support extended predetection integration. Given that the implementation is done in software, it would be expect to be used in many future INS/GPS implementations.

5.0 INS/GPS Interference Issues

Interference to the reception of GPS signals can be due to many causes such as telecommunication devices, local interference from signals or oscillators on the same platform, or possibly radar signals in nearby frequency bands. Attenuation of the GPS signal can be caused by trees, buildings, or antenna orientation, and result in reduced signal/noise ratio even without interference. This loss of signal can result in an increase in effective jammer/signal (J/S) level even without intentional jamming or interference. The minimum received signal power at the surface of the Earth is about -155dBW, a level easily overcome by a jammer source.

Military receivers are at risk due to intentional jamming. Jammers as small as 1 W located at 100 km from the receiver can possibly prevent a military receiver from acquiring the satellite signals and "locking-on" to C/A code. Representative jammers are shown in Figure 16. Larger jammers are good targets to find and to attack because of their large radiation. Smaller jammers, which are hard to find, need to be defended against by improved anti-jam (A/J) technologies within the receiver, improved antennas, or by integration with an inertial navigation system. Proponents of high-accuracy inertial systems will generally argue that a high anti-jam GPS receiver is not required, while receiver proponents will argue that using a higher A/J receiver will substantially reduce inertial system accuracy requirements and cost. Both arguments depend entirely on the usually ill-defined mission and jamming scenario.

What has generally become accepted is that the GPS is remarkably vulnerable to jamming during the C/A code acquisition phase where conventional receiver technology has only limited jammer tolerability (J/S - 27 dB) (Refs. [10], [11], [12]). A 1-W (ERP) jammer located at 100 km from the GPS antenna terminals could prevent acquisition of the C/A code. Figure 17 is very useful in determining trade-offs between required A/J margin and jammer power. A 1-W jammer is "cheap" and potentially the size of a hockey puck. Furthermore, the C/A code can be spoofed by an even smaller power jammer. So generally, a GPS receiver cannot be expected to acquire the C/A code in a hostile environment.

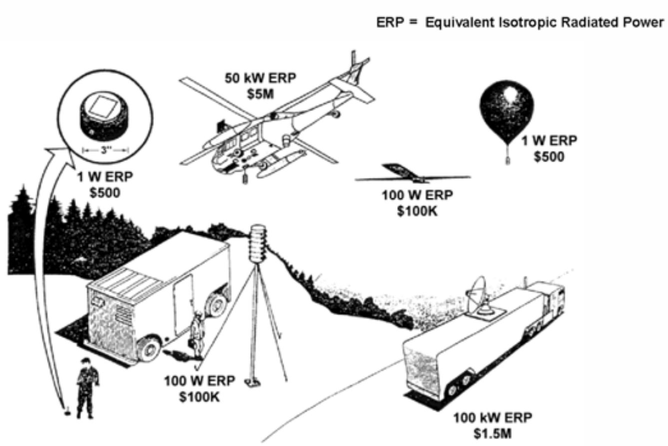


Figure 16. Jammer possibilities.

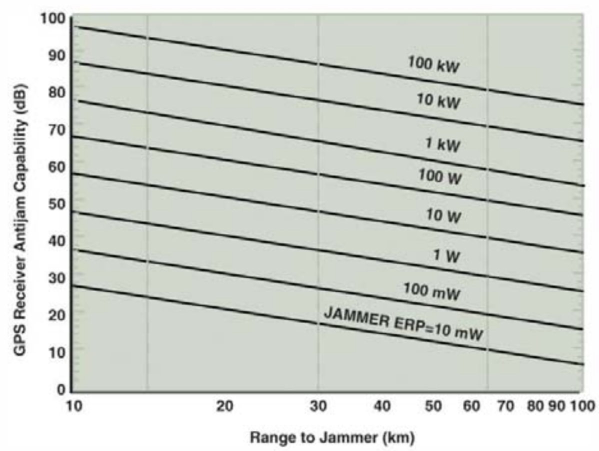


Figure 17. GPS jamming calculations.

For long-range cruise missile type applications, the C/A code could be acquired outside hostile territory and then the receiver would transition to P(Y) code lock, which has a higher level of jamming immunity. A 1-kW (ERP) jammer at about 100 km would now be required to break inertially-aided receiver code lock at 54 to 57 dB. As the weapon approaches the jammer, jammer power levels of about 10 W would be effective in breaking P(Y) code lock at 10 km (see Figure 18).

As previously mentioned, the "deeply integrated" architecture for combining INS and GPS may allow for tracking GPS satellites up to 70 – 75 dB J/S, an improvement of 15 to 20 dB above conventional P(Y) code tracking of 54 to 57 dB. If future increases of 20 dB in broadcast satellite power using the M-code spot beam (M spot) are also achieved, nearly 40 dB of additional performance margin would be achieved, so a jammer of nearly 100 kW would be required to break lock at 10 km. Furthermore, new receiver technology with advanced algorithms and space-time adaptive or nulling antenna technologies might also be incorporated into the system, further increasing its A/J capability significantly.

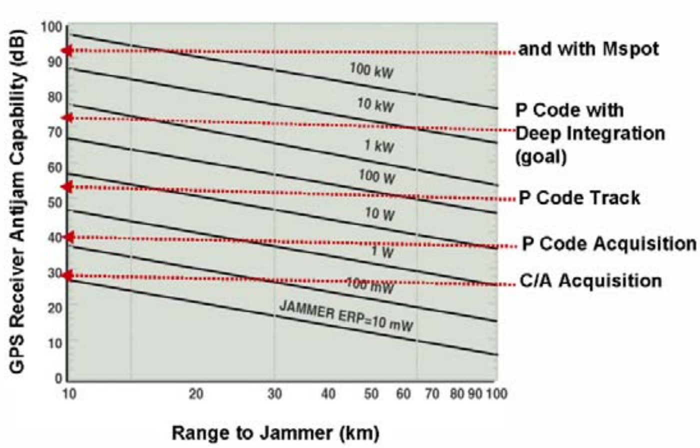


Figure 18. Possible A/J capabilities.

Recently (Ref. [3]) Honeywell and Rockwell Collins created a joint venture, Integrated Guidance Systems LLC, to market and produce deeply integrated guidance systems. The IGS-200 is G-hardened for artillery applications (15,750G), has a volume 13.7 in^3, weighs < 1 lb., is based on the 1930G Honeywell MEMS IMU, and with deep integration and 2-channel digital nulling, the system supposedly has 80 – 90 dB J/S against a single jammer.

If A/J performance is increased significantly, then the jammer power must also be increased significantly. A large jammer would present an inviting target to an antiradiation, homing missile. In the terminal area of flight against a target, the jammer located at the target will eventually jam the receiver, and the vehicle will have to depend on inertial-only guidance or the use of a target sensor. Thus, it is important to ensure that accurate guidance and navigation capability is provided to meet military mission requirements against adversaries who are willing to invest in electronic countermeasures (ECM). This fact is true today and is expected to remain so in the foreseeable future. Figure 19 summarizes electronic counter-countermeasures (ECCM) techniques.

- **Lower Cost, High-Accuracy IMU's**
- **Improve Signals in Space**
  - Increased Accuracy
  - Mcode and Mspot
- **Improved Receivers**
  - Deep Integration With IMU
  - Anti-Spoof Techniques
  - Higher A/J Electronic
- **Direct P (Y) Code Acquisition, Lock-on Before Launch**
  - Improved Aircraft Interface To Munitions
  - Miniature On-board Clock
  - Multiple Correlators
- **Higher Performance, Lower Cost Adaptive Antennas**
  - Digital Beamforming
  - Modern Algorithms

Figure 19. Valuable ECCM technologies and techniques.

6.0 Concluding Remarks

Recent progress in INS/GPS technology has accelerated the potential use of these integrated systems, while awareness has also increased concerning GPS vulnerabilities to interference. In the near future, improvements in accuracy in the broadcast GPS signals will evolve to 1 m. Many uses will be found for this high accuracy. In parallel, lower-cost inertial components will be developed and they will also have improved accuracy. Highly integrated A/J architectures for INS/GPS systems will become common, replacing avionics architectures based on functional black boxes where receivers and inertial systems are treated as stand-alone systems.

For future military and civilian applications, it is expected that the use of INS/GPS systems will proliferate and ultimately result in worldwide navigation accuracy better than 1 m, which will need to be maintained under all conditions. It can be expected that applications such as personal navigation systems, micro air vehicles (MAV), artillery shells, and automobiles will be quite common, see Figure 20. Other applications will certainly include spacecraft, aircraft, missiles, commercial vehicles, and consumer items.

Figure 20. Examples of potential applications.

Acknowledgments/Additional References

Thanks to Neil Barbour for assistance with the section on Inertial Sensor Trends. A history of inertial navigation is given in Ref. [14] and a history of the GPS program is given in Ref. [15].

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14. Abstract

The NATO Research and Technology Organization (RTO) Research Task Group (RTG) on Urban, Indoor and Subterranean Navigation Sensors and Systems (SET-114, RTG-065) was formed to focus on how to enhance NATO military effectiveness through the improved use of advanced navigation sensor technologies. This report summarizes the work of the RTG, includes a description of the products generated by the group and provides a detailed technical overview of new and emerging navigation sensor and system integration technologies that will impact future NATO military operations worldwide.

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